Energy Correlator for Hadronic Structures

Xiaohui Liu
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味物理讲座, Oct 10, 2024

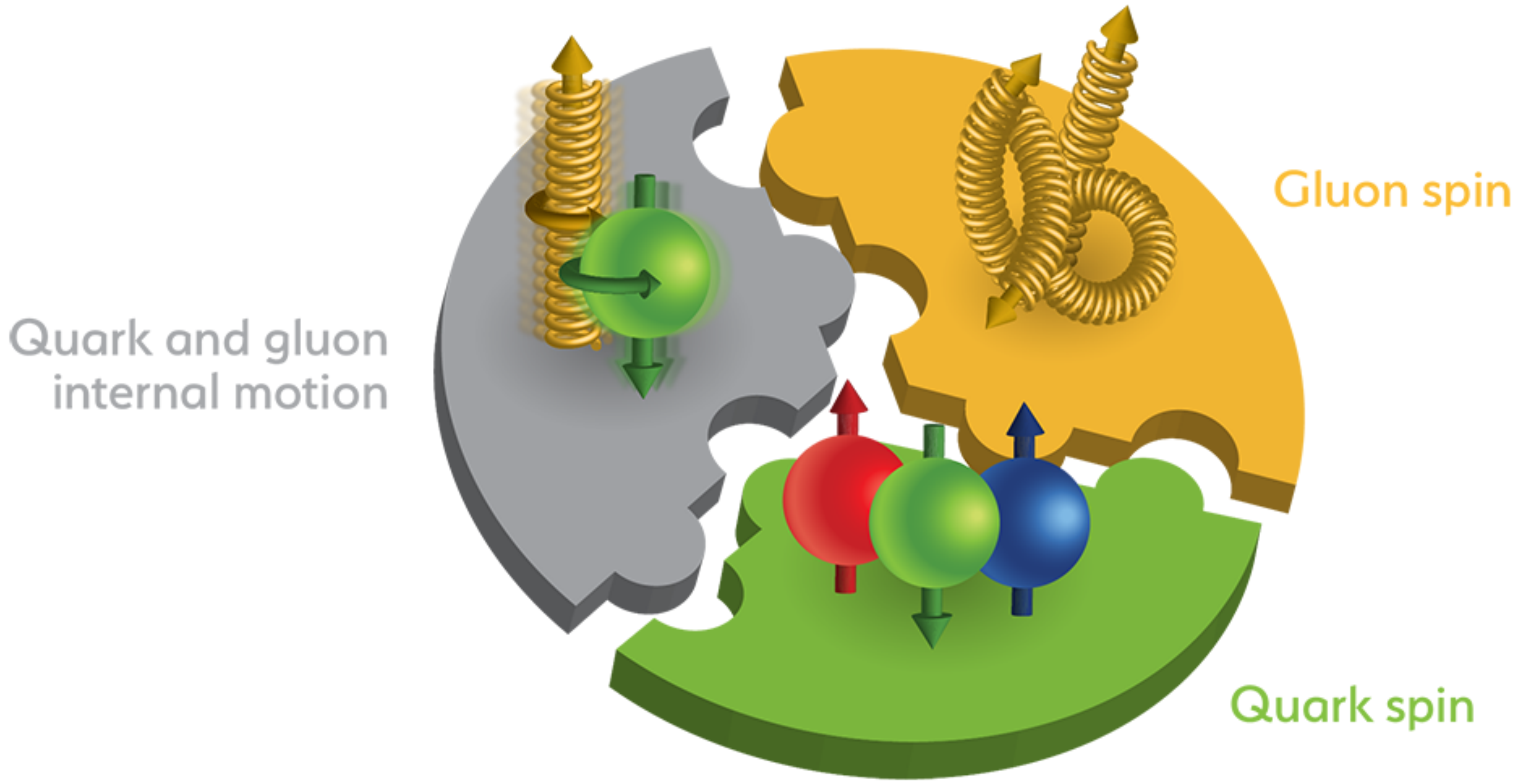
XL and Zhu, **PRL** 130 (2023), 9, 9
Liu, XL, Pan, Yuan and Zhu, **PRL** 130 (2023) 18, 18
Cao, XL and Zhu, **PRD** 107 (2023) 11, 114008
Chen, XL and Ma, **PRL** (2024) accepted + …

BEIJING NORMAL UNIVERSITY

Outline

- Non-perturbative Structure studies
- Energy Correlator
- Nucleon energy Correlators (NECs)
  - Definition, measurement, factorization and properties
  - Phenomenology
- Quarkonium Energy Correlator
- New insights into the non-perturbative structures ???

Structure Studies



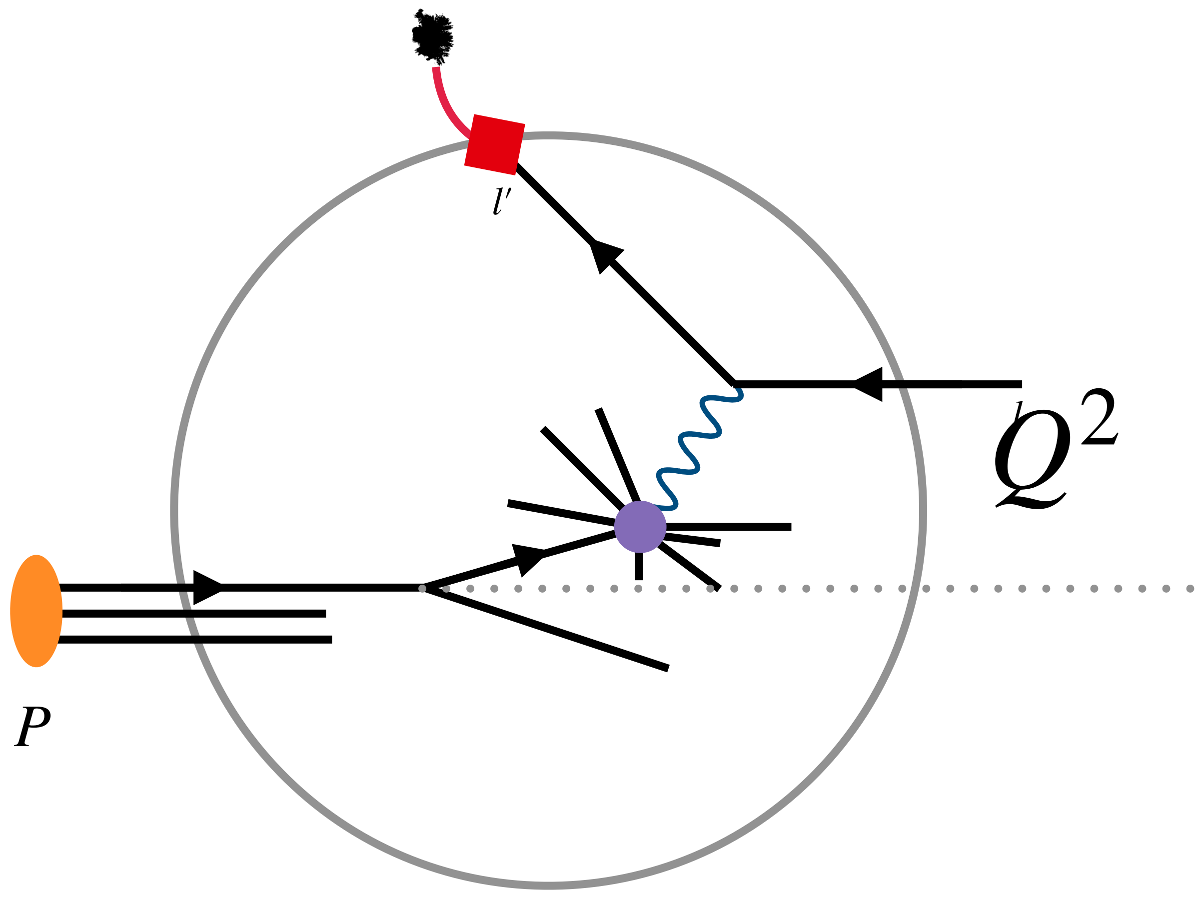
Major focus of the EicC, EIC …

Structure Studies

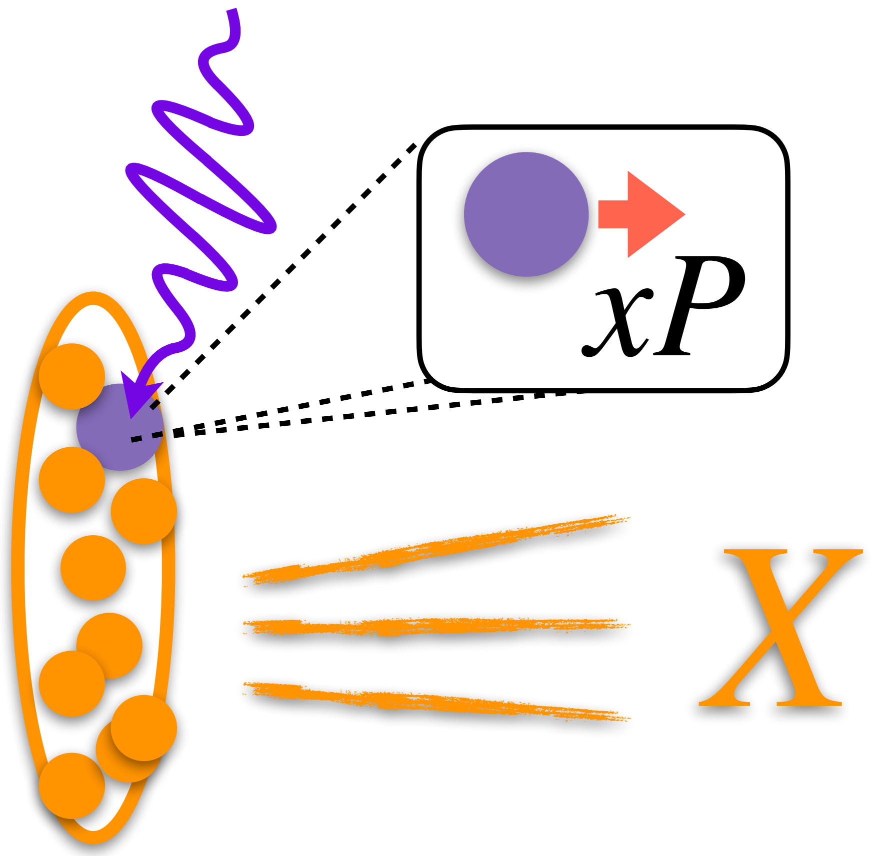
Collinear Parton Distribution Functions (PDFs)

$$f_{q/p}(x) = \int_{-\infty}^{\infty} \frac{dy^-}{2\pi} e^{ixp^+y^-} \frac{\gamma^+}{2} \langle P | \bar{\psi}(0) \mathscr{L} \psi(y^-) | P \rangle$$

$$\propto \delta(xP - p) \langle P | a_q^\dagger a_q | P \rangle$$



DIS

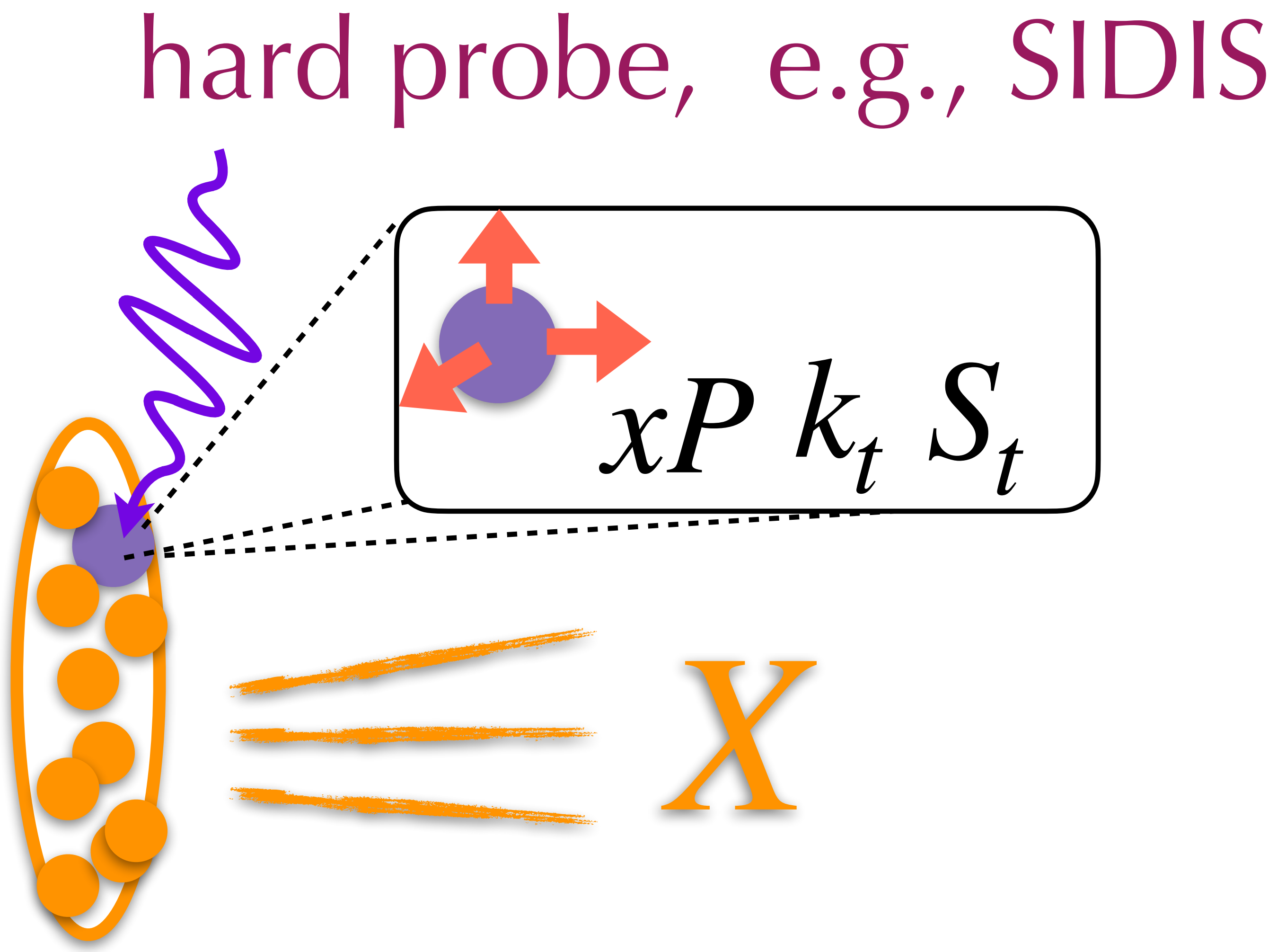


- inclusive over X, clean.
- not differential enough, lose information

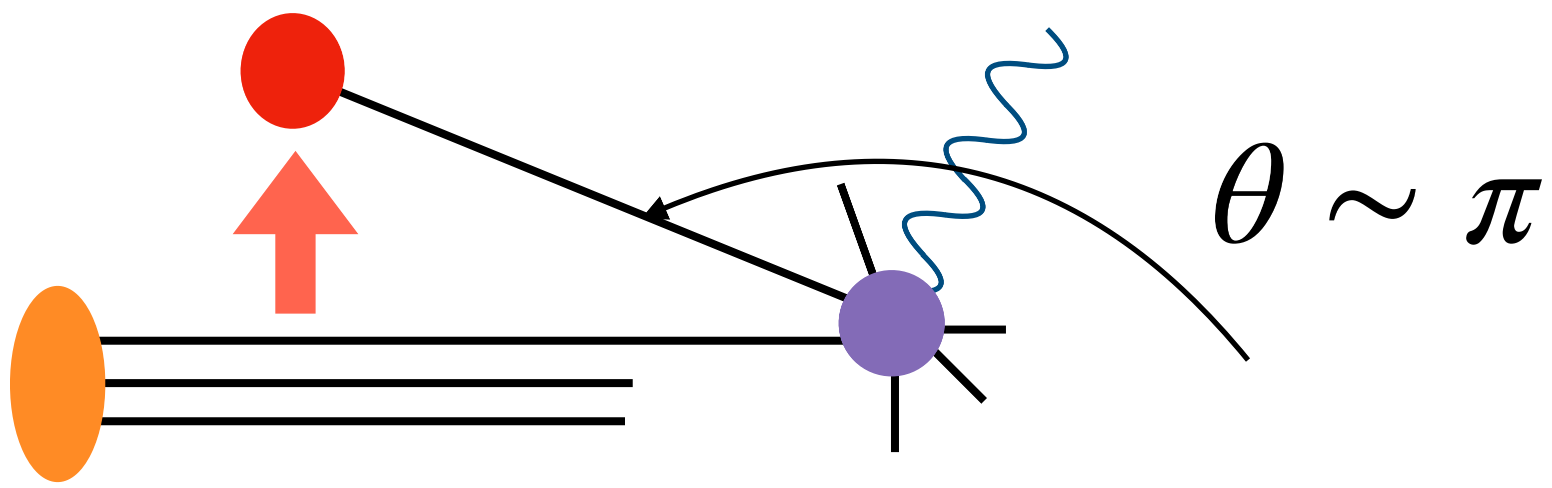
Structure Studies

Transverse Moment Dependent-PDFs (TMDs)

$$f_{q/p}(x,k_t) = \int_{-\infty}^{\infty} \frac{dy^- dy_t}{(2\pi)^3} e^{ixp^+y^-} e^{ik_t\cdot y_t} \frac{\gamma^+}{2} \langle P | \bar{\psi}(0) \mathscr{L} \psi(y_t, y^-) | P \rangle$$



$$q_t \sim k_t \sim \Lambda_{\rm QCD}$$



SIDIS, Breit Frame

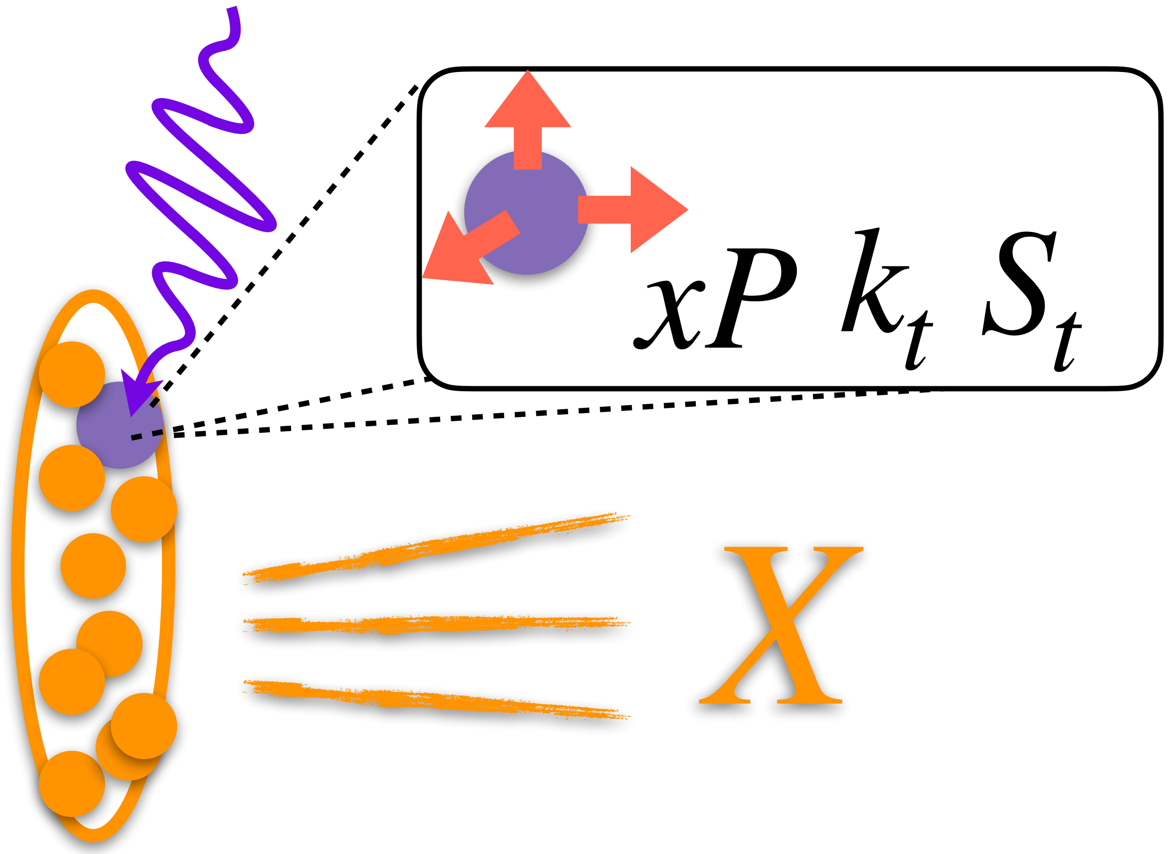
- Major tool for structure studies
- Enforce the b-to-b configuration

Structure Studies

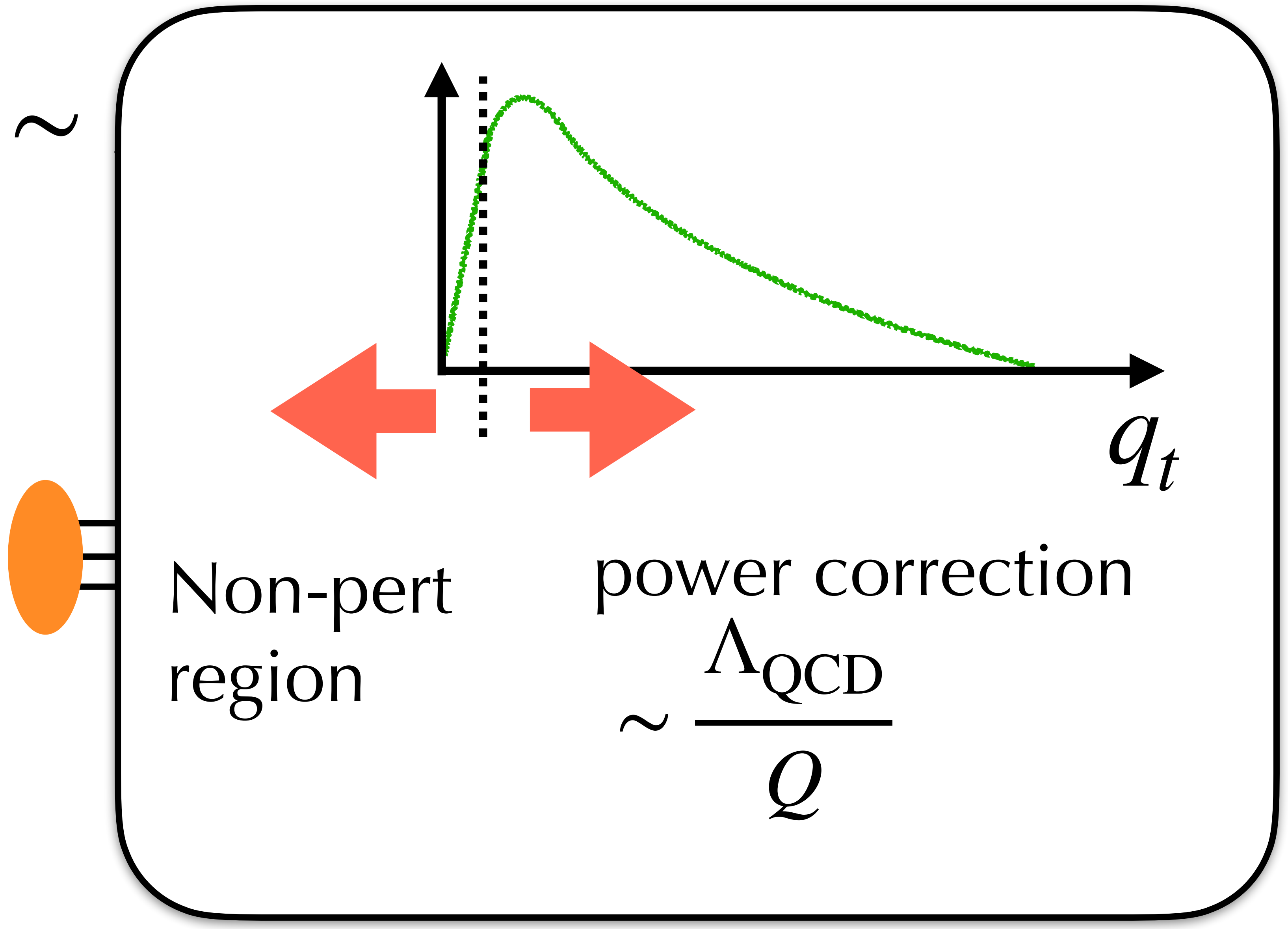
Transverse Moment Dependent-PDFs (TMDs)

$$f_{q/p}(x, k_t) = \int_{-\infty}^{\infty} \frac{dy^- dy_t}{(2\pi)^3} e^{ixp^+y^-} e^{ik_t \cdot y_t} \frac{\gamma^+}{2} \langle P | \bar{\psi}(0) \mathscr{L} \psi(y_t, y^-) | P \rangle$$

hard probe, e.g., SIDIS



$q_t \sim k_t \sim$



- Major tool for structure studies
- Soft contamination
  - Sudakov suppression $\sigma(k_T) \propto \frac{1}{q_t^2} e^{-\frac{Q^2}{q_T^2}}$
  - Distort azimuthal asymmetry

Hatta, Xiao, Yuan, Zhou, PRL 2021

Structure Studies

Transverse Moment Dependent-PDFs (TMDs)

$$f_{q/p}(x, k_t) = \int_{-\infty}^{\infty} \frac{dy^- dy_t}{(2\pi)^3} e^{ixp^+y^-} e^{ik_t \cdot y_t} \frac{\gamma^+}{2} \langle P | \bar{\psi}(0) \mathscr{L} \psi(y_t, y^-) | P \rangle$$

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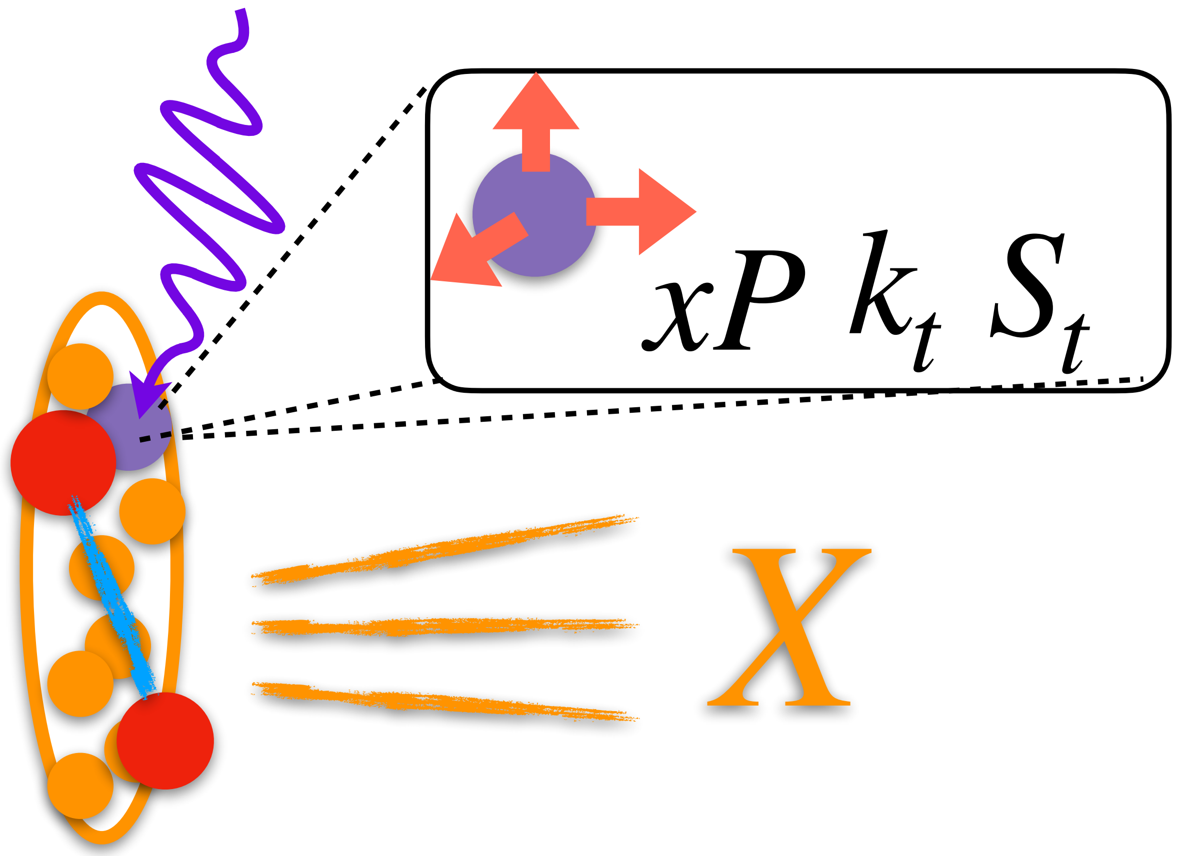
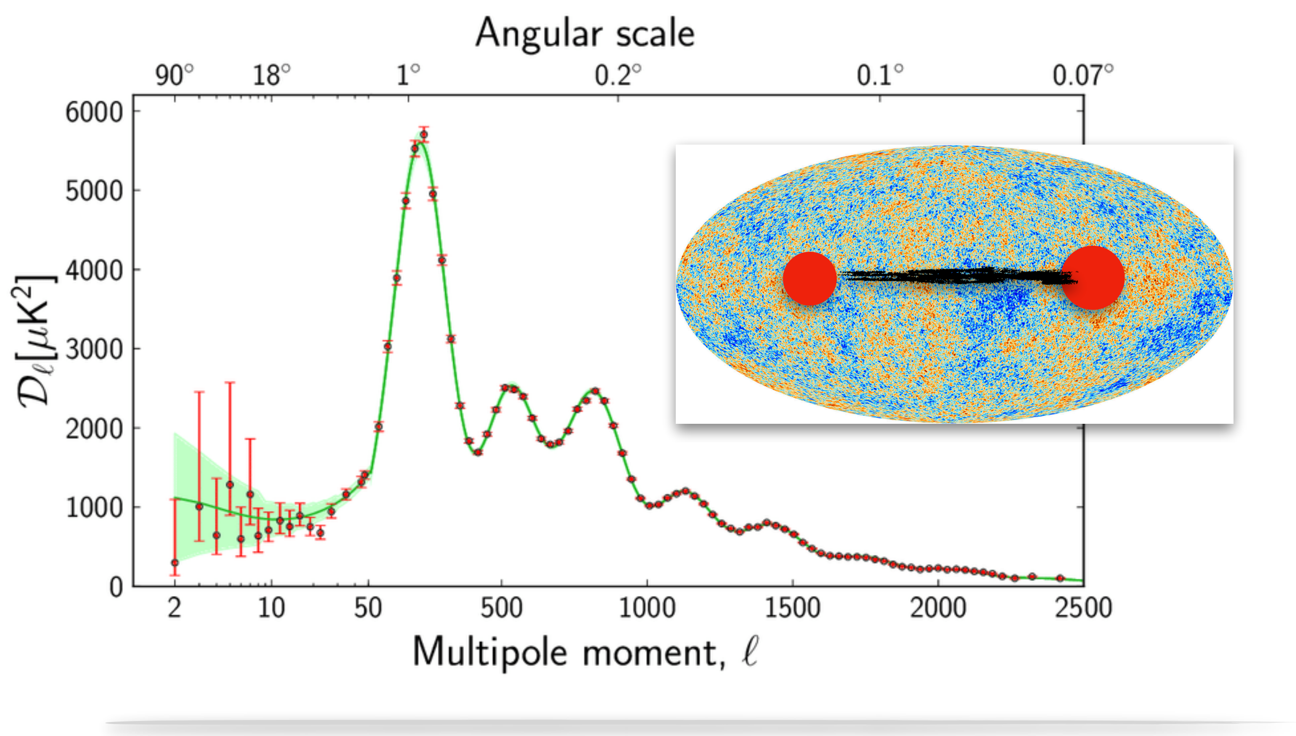


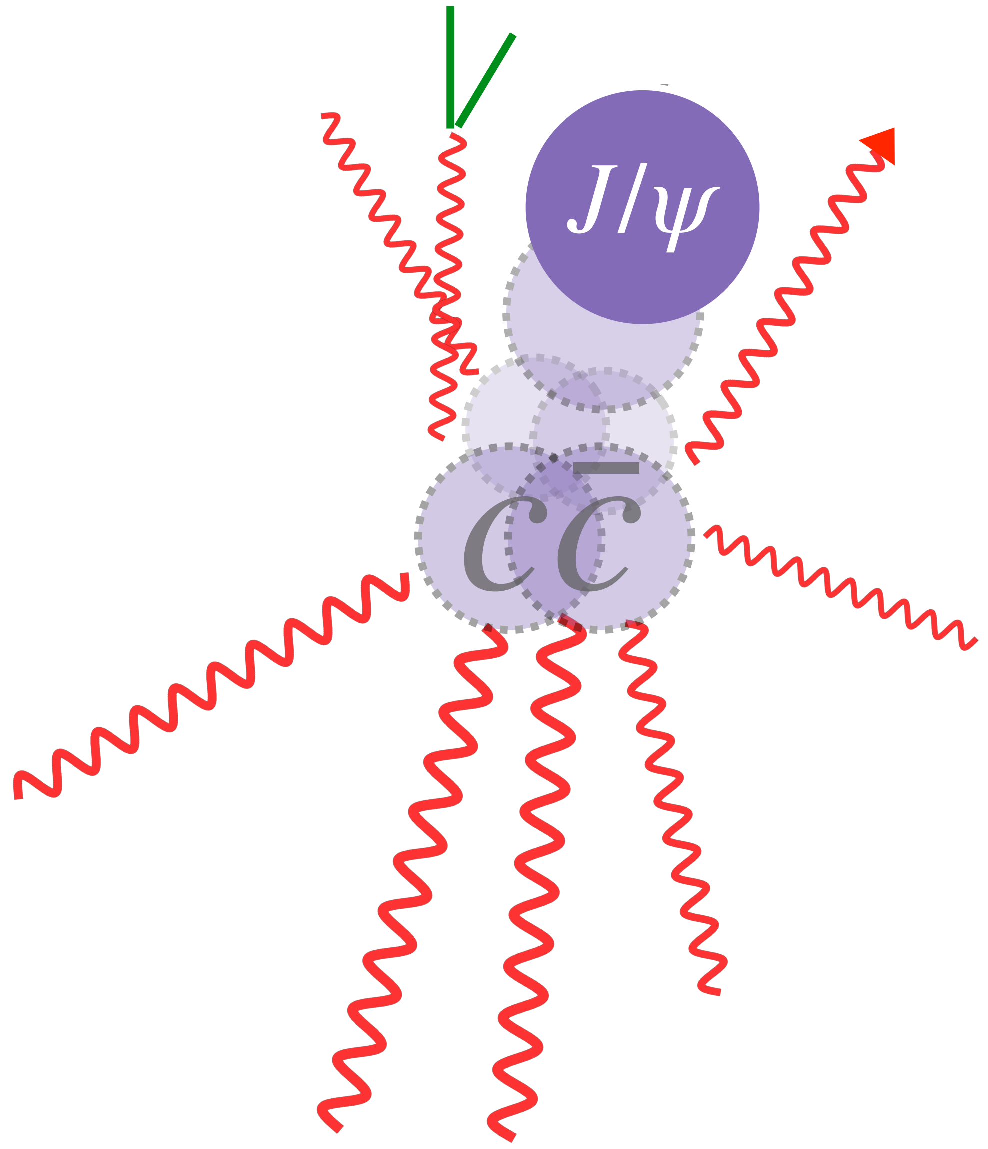


$\delta T(n_1) \delta T(n_2)$

- Still lose information

Structure Studies

- How $c\bar{c} \to J/\psi$?
  - NRQCD: encoded in $\langle \mathcal{O}_\mathbf{1} \rangle$, $\langle \mathcal{O}_\mathbf{8} \rangle$
    - remains largely unknown: amount of energy released? Energy Distribution?

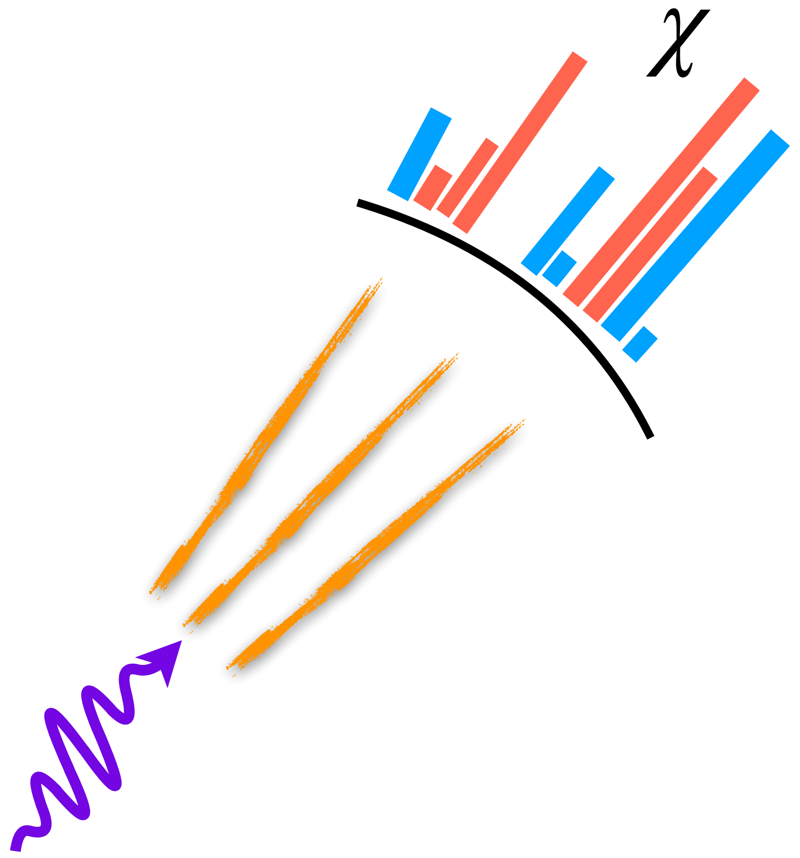


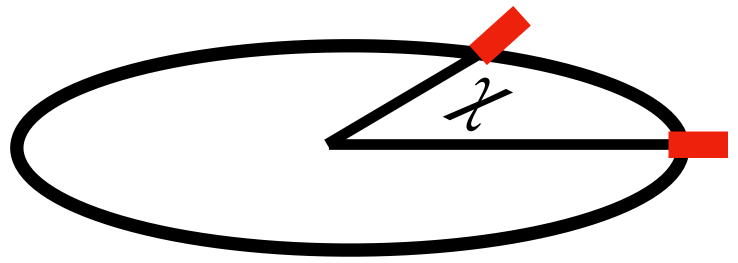
Energy Correlator

Andres, Basham, Belitsky, Brown, H Chen, Dixon, Dominguez, Elayavalli, Ellis, J Gao, Hofman, Hohenegger, Holguin, Jaarsma, ZB Kang, Kologlu, Korchemsky, Kravchuk, Komiske, Lee, HT Li, YB Li, Love, MX Luo, Maldacena, Meçaj, Marquet, Moult, Pathak, Procura, DY Shao, Simmons-Duffin, Sokatchev, Thaler, van Velzen, W. Wang, X-N Wang, Waalewijn, M Xiao, K Yan, TZ Yang, F Yuan, Zhang, Zhiboedov, HX Zhu + …

Energy Correlators

Energy-Energy-Correlator (EEC)

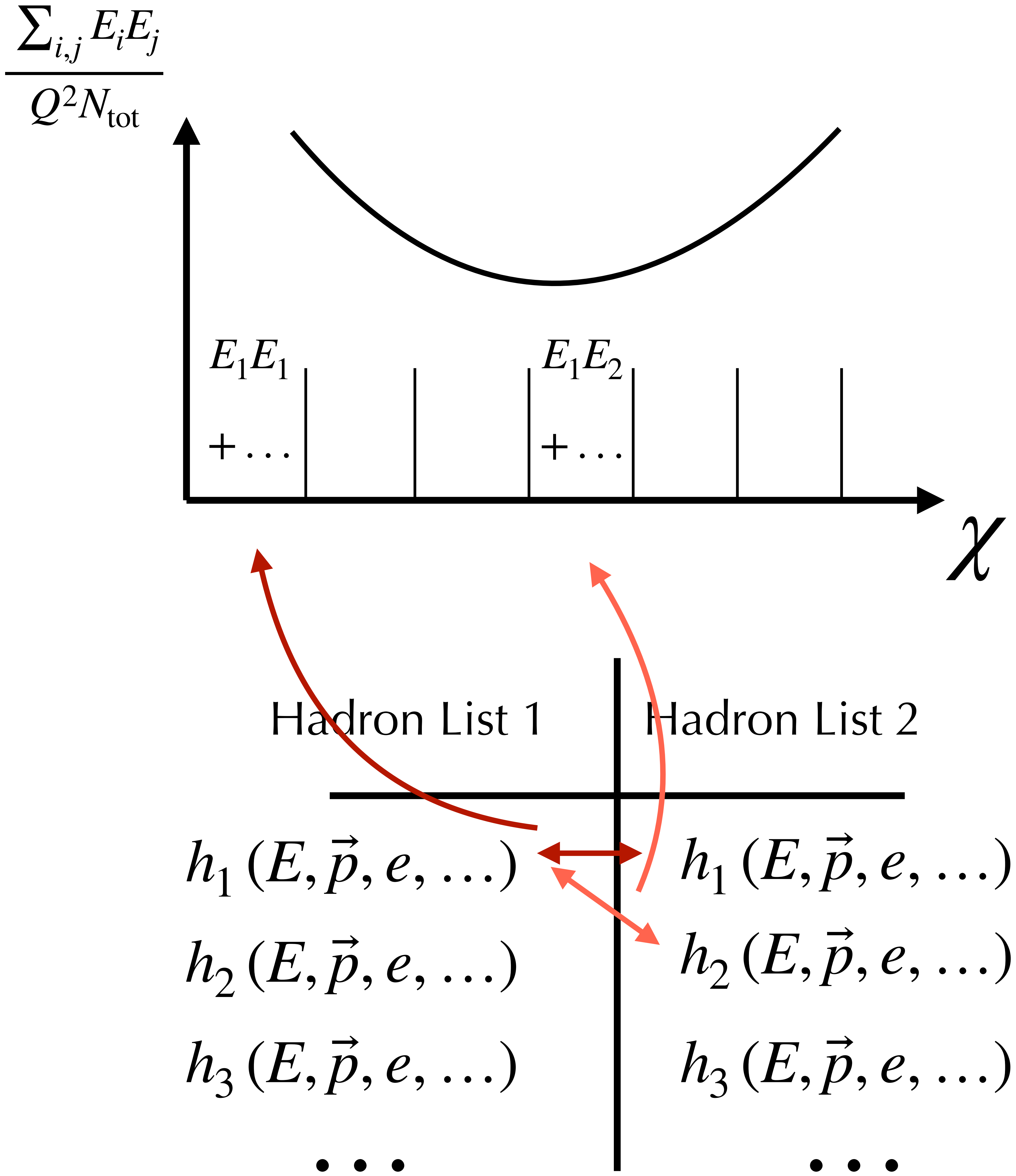




$$\Sigma_{\mathrm{EEC}} = \frac{1}{\sigma}\int d\sigma \sum_{ij} \frac{E_i E_j}{Q^2}\delta(\chi - \theta_{ij})$$

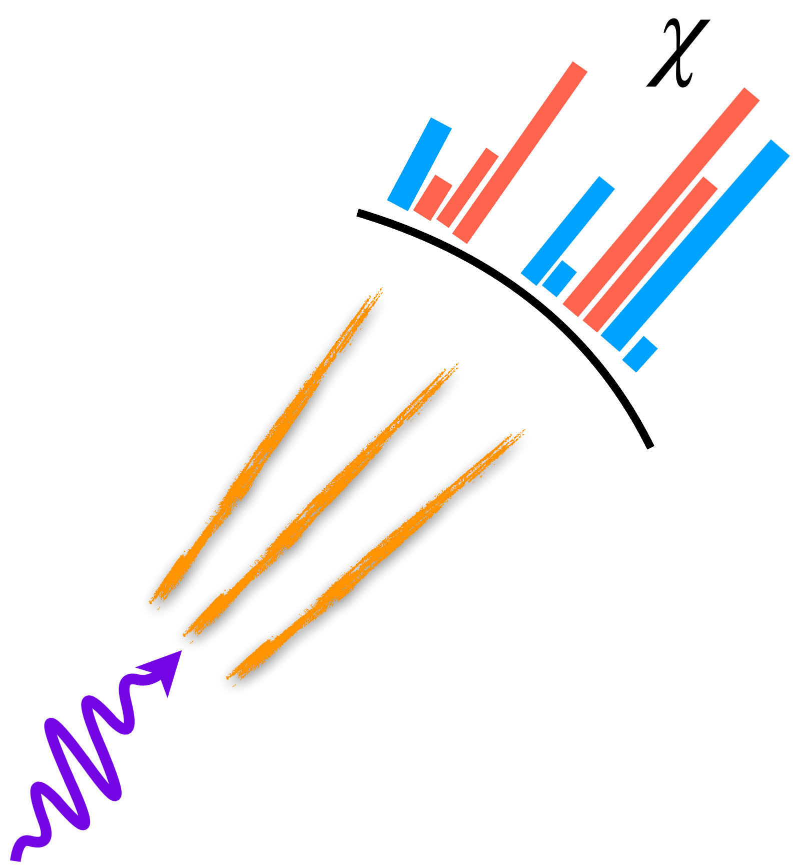
Sterman, 1975

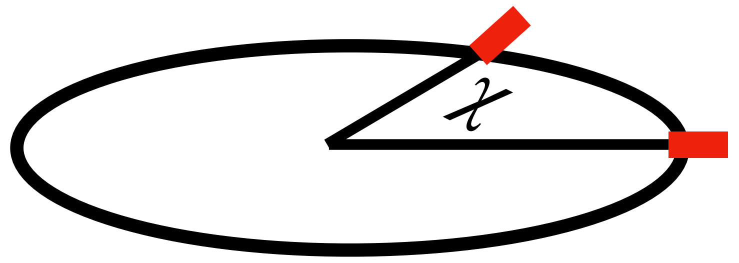
Bashman, et al. 1978



Energy Correlators

Energy-Energy-Correlator (EEC)





$$\mathcal{E}(n) = \int_0^\infty dt \lim_{r\to\infty} T_{0\vec{n}}(t, \vec{n}r)r^2$$

detector by the light-ray operator

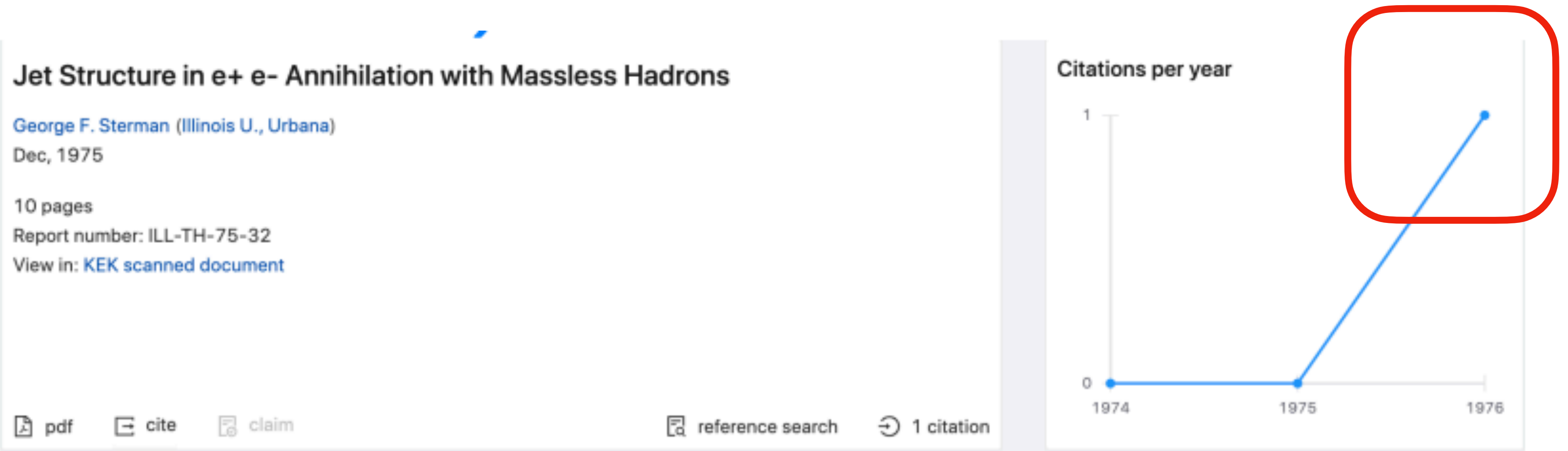
$$\Sigma_{\rm EEC} = \frac{1}{\sigma}\int d\sigma \sum_{ij} \frac{E_i E_j}{Q^2}\delta(\chi - \theta_{ij})$$

$$= \frac{1}{Q^2}\langle J^\mu(x)\mathcal{E}(n_1)\mathcal{E}(n_2)J^\nu(0)\rangle_\Omega$$

- Easy to implement, **"Jet w/o jet"**
- Perturbatively predictable

  e.g., Gao, Li, Moult, Zhu, 2023, Chen, et al. 2024
- Dual description

Energy Correlators



Our ensembles will thus be specified in terms of set

states. To make this idea more quantitative we defi

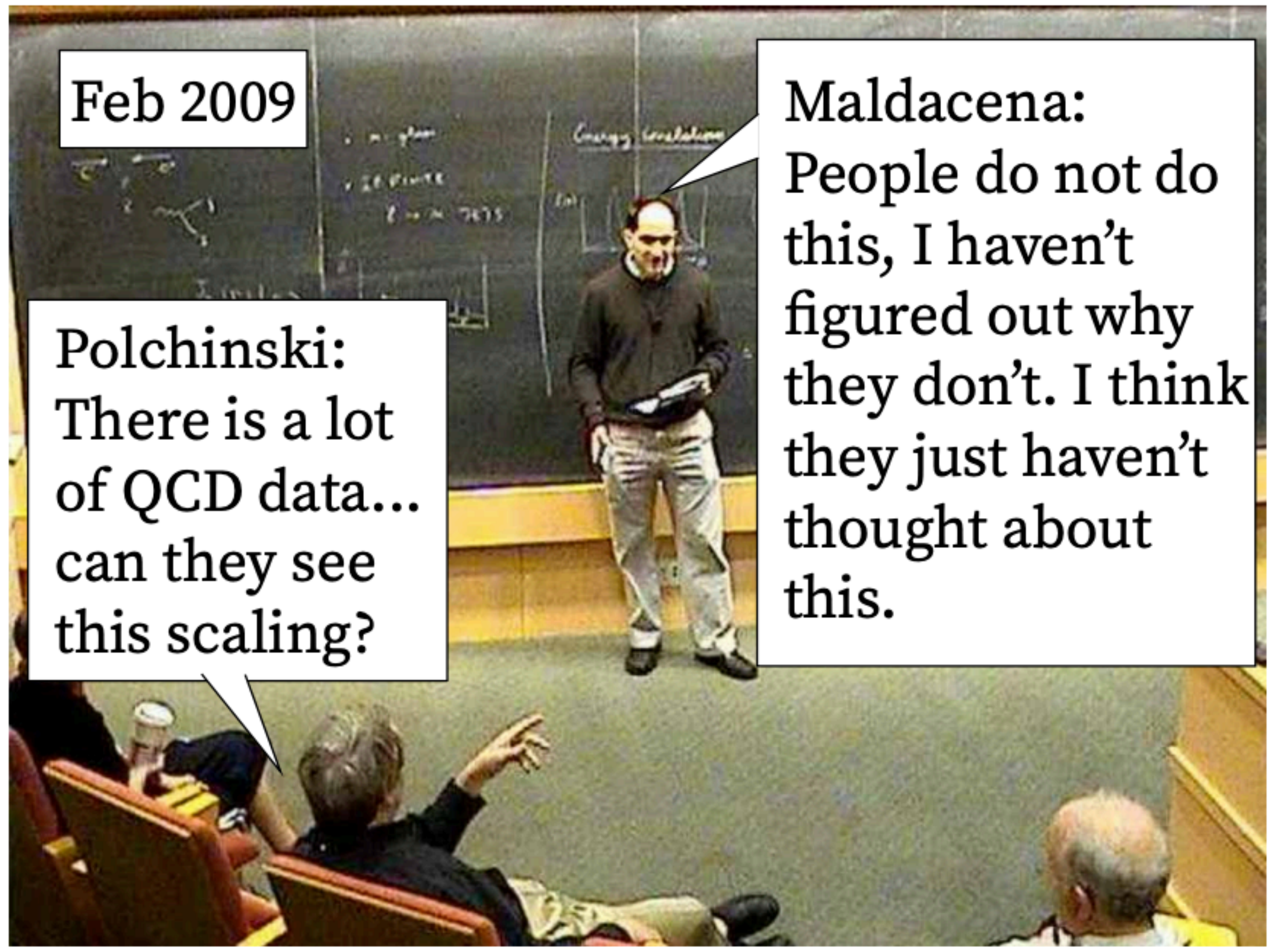
"angular energy current" in the e^+e^- CM frame:

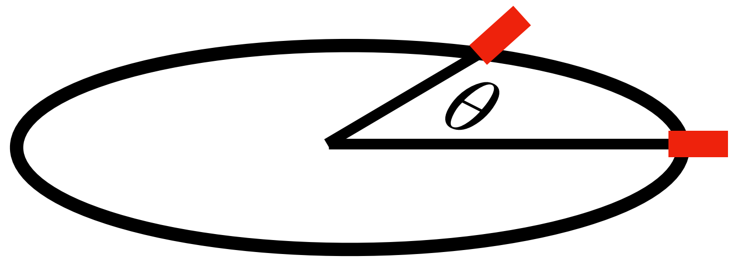
$$j_a(\Omega) = \sum_{i=1}^{n_a} \eta_i \delta(\Omega - \omega_i)$$

Conformal collider physics:
Energy and charge correlations

Diego M. Hofman[a] and Juan Maldacena[b]

[a] *Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544, USA*
[b] *School of Natural Sciences, Institute for Advanced Study*
Princeton, NJ 08540, USA





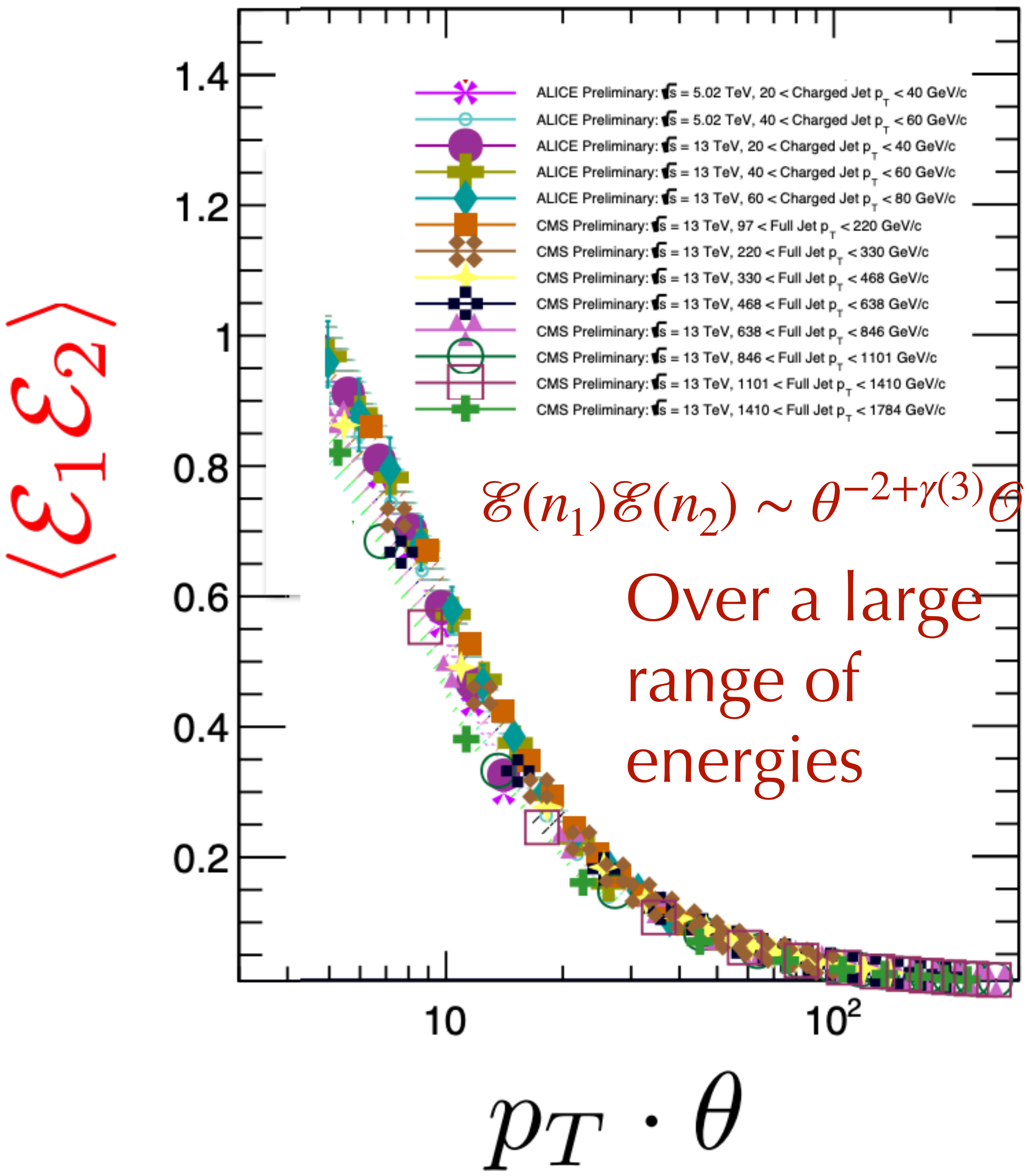
$$\mathcal{E}(n_1)\mathcal{E}(n_2) \sim \theta^{-2+\gamma(3)}\mathcal{O}, \theta \to 0$$

Ian Moult, MITP talk 2024

Scaling rule by conformal theory Hofman, Maldecena, 2008

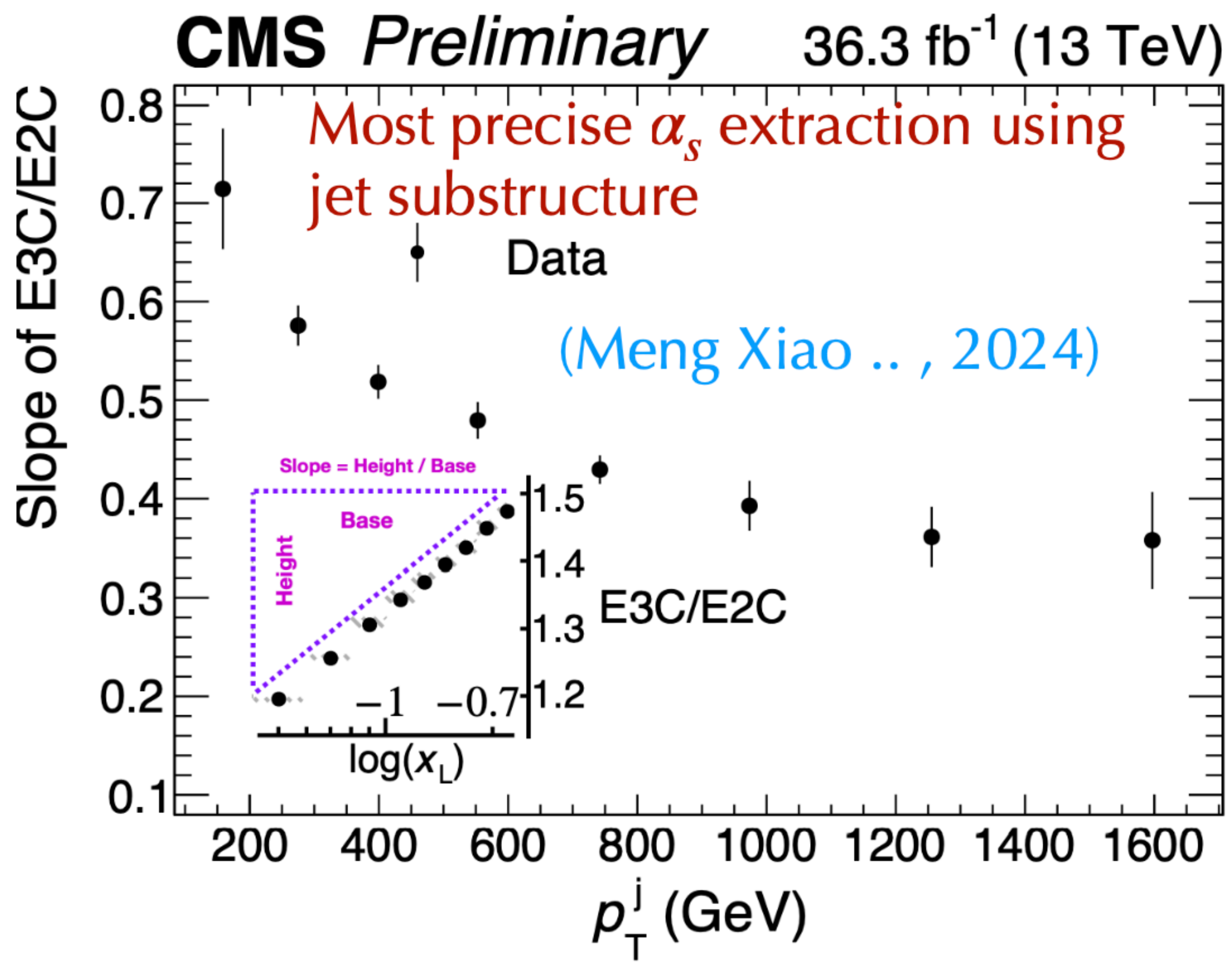
Energy Correlators

As of 2024



$\mathscr{E}(n_1)\mathscr{E}(n_2) \sim \theta^{-2+\gamma(3)}\mathcal{O}$

Over a large range of energies

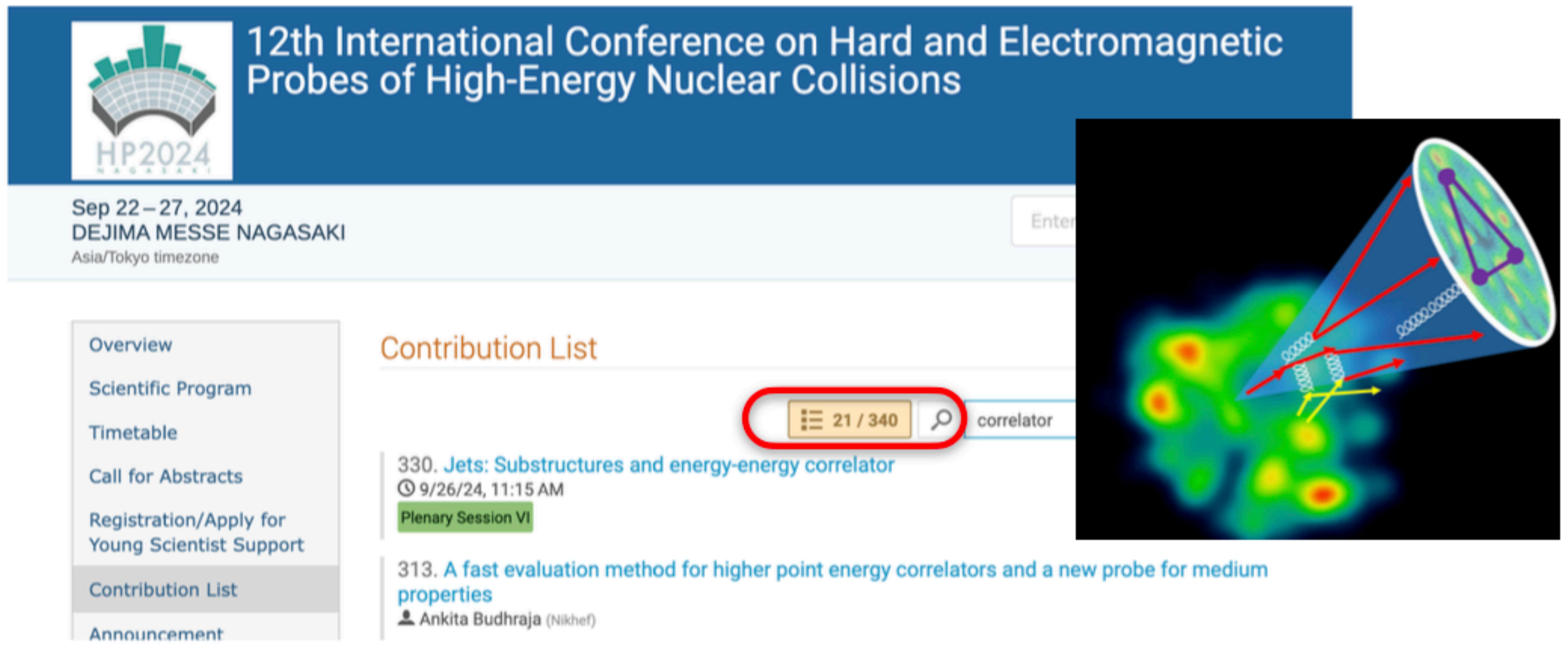


Most precise α_s extraction using jet substructure

(Meng Xiao .. , 2024)

Yang, He, Moult, Wang, 2024 PRL + …

A new probe of QGP



12th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

HP2024

Sep 22 – 27, 2024
DEJIMA MESSE NAGASAKI
Asia/Tokyo timezone

Overview
Scientific Program
Timetable
Call for Abstracts
Registration/Apply for Young Scientist Support
Contribution List
Announcement

Contribution List

21 / 340 correlator

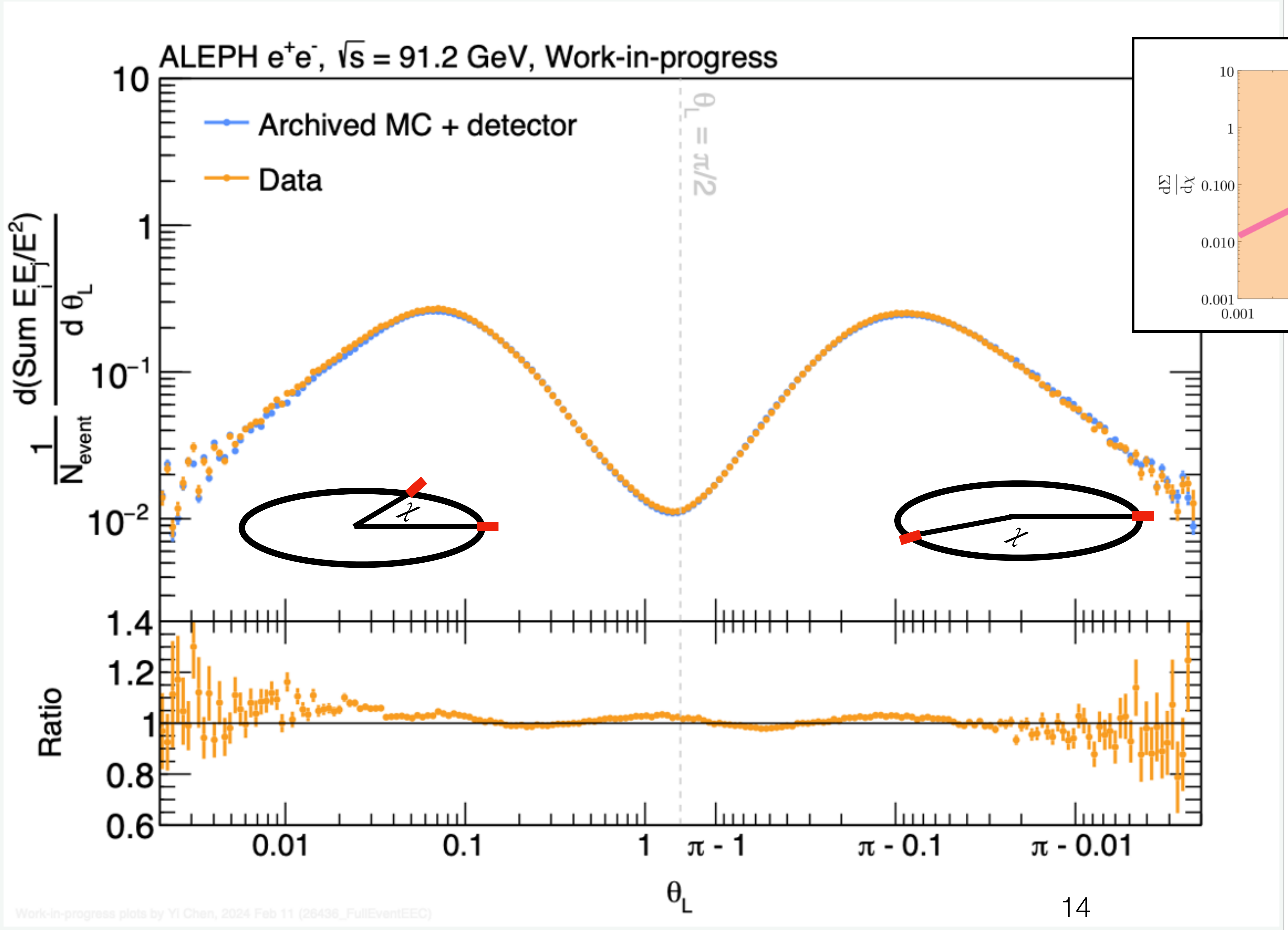
330. Jets: Substructures and energy-energy correlator
9/26/24, 11:15 AM
Plenary Session VI

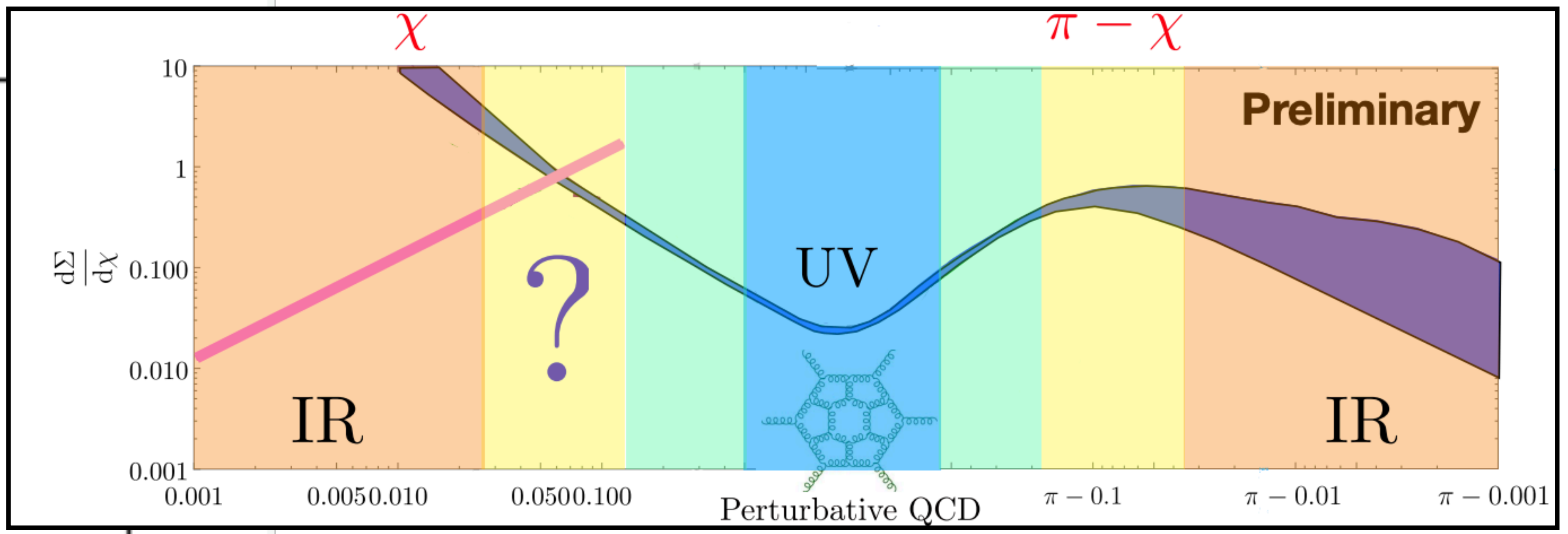
313. A fast evaluation method for higher point energy correlators and a new probe for medium properties
Ankita Budhraja (Nikhef)

Energy Correlators

Full Spectrum with high precision

Yen-Jie Lee, MITP talk 2024



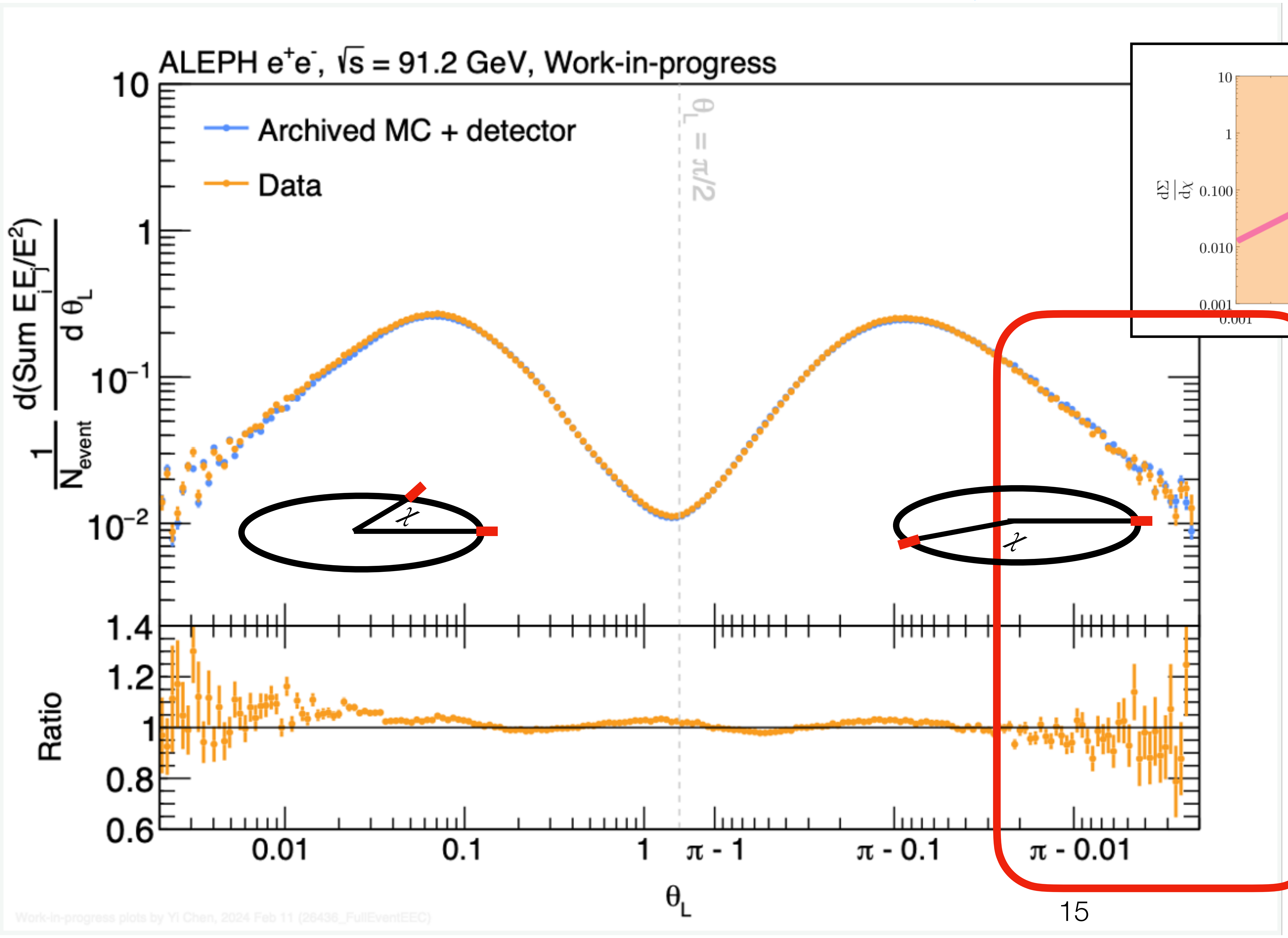


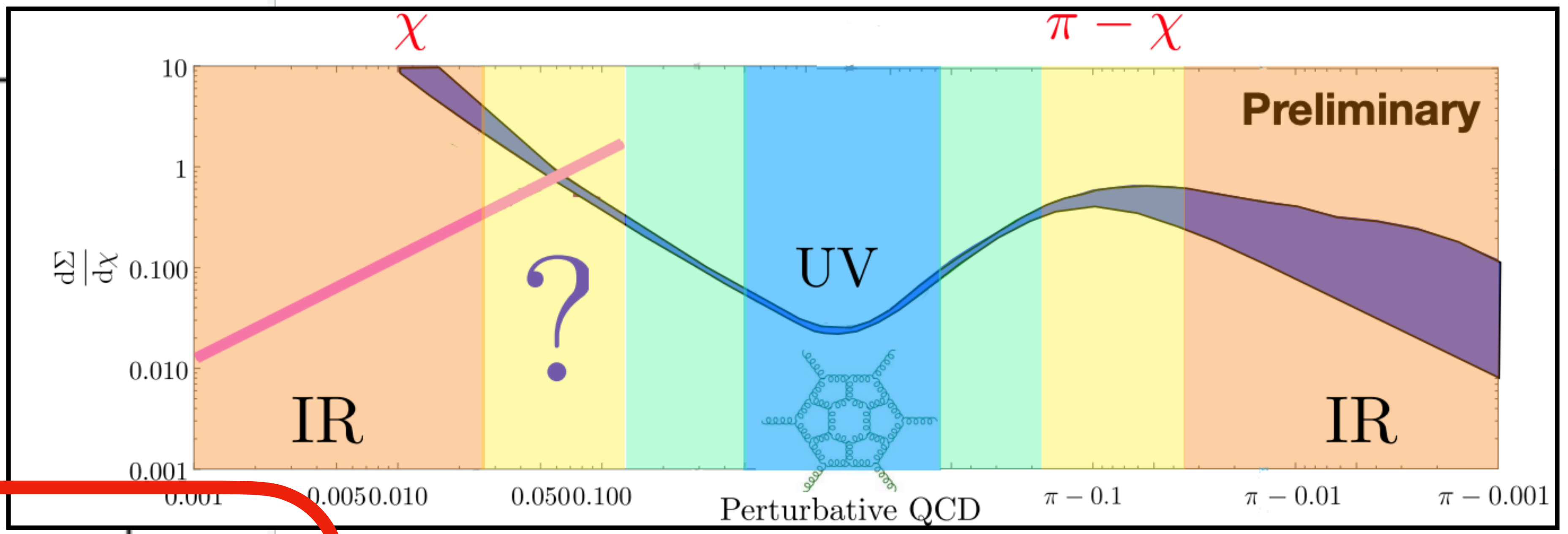
- Accidentally symmetric
- Different physics in different regions

Energy Correlators

Full Spectrum with high precision

Yen-Jie Lee, MITP talk 2024





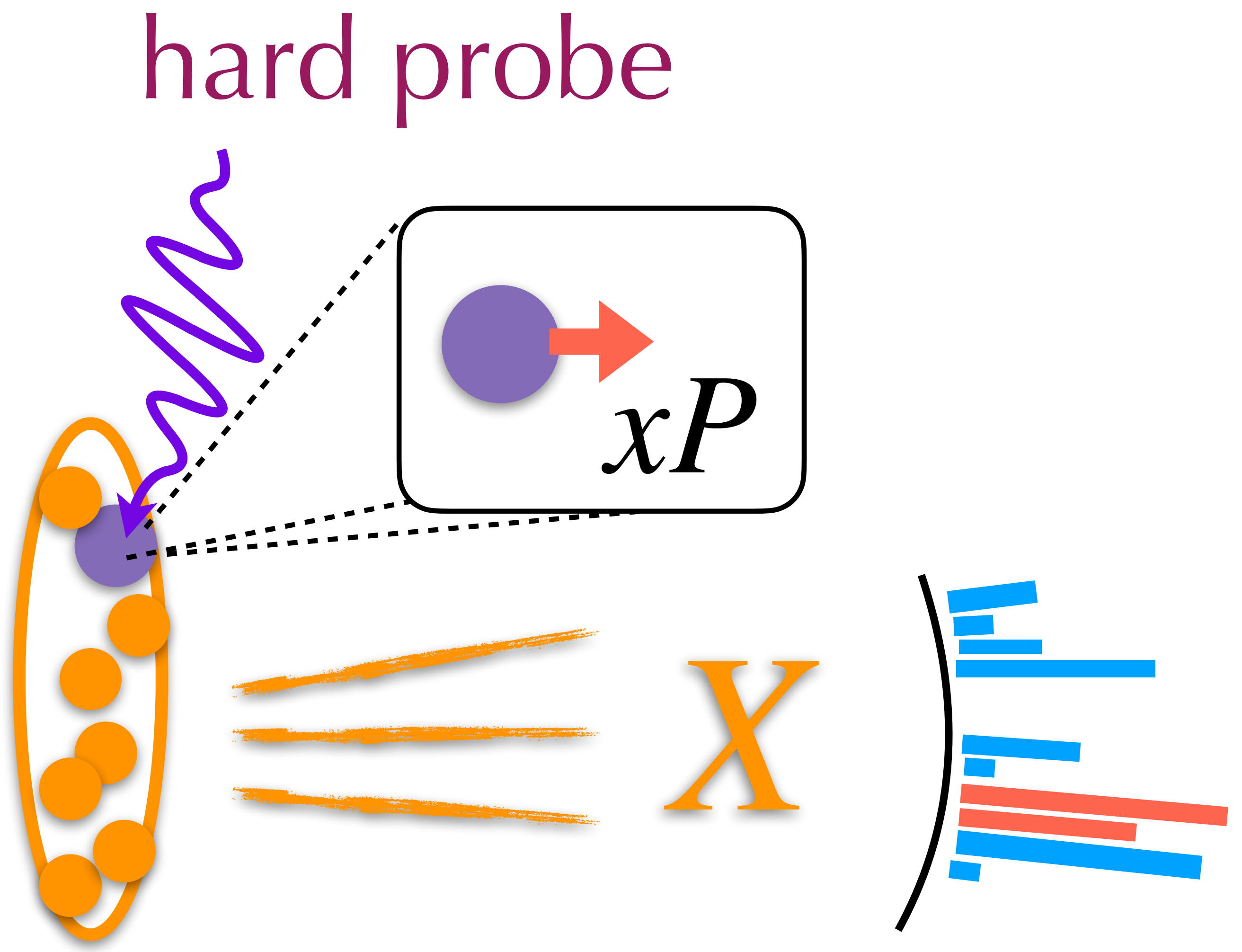
Can be used for the possible most precise extraction of the NP TMD Sudakov Factor !

Nucleon Energy Correlator

Operator Definition

Nucleon EEC XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9

$$f_{q,EEC}(x,\theta) = \int_{-\infty}^{\infty} \frac{dy^-}{2\pi} e^{ixp^+y^-\frac{\gamma^+}{2}} \langle P | \bar{\psi}(0) \mathcal{E}(\theta) \mathcal{L} \psi(y^-) | P \rangle$$



$$\mathcal{E}(n) = \int_0^{\infty} dt \lim_{r\to\infty} T_{0\vec{n}}(t, \vec{n}r) r^2$$

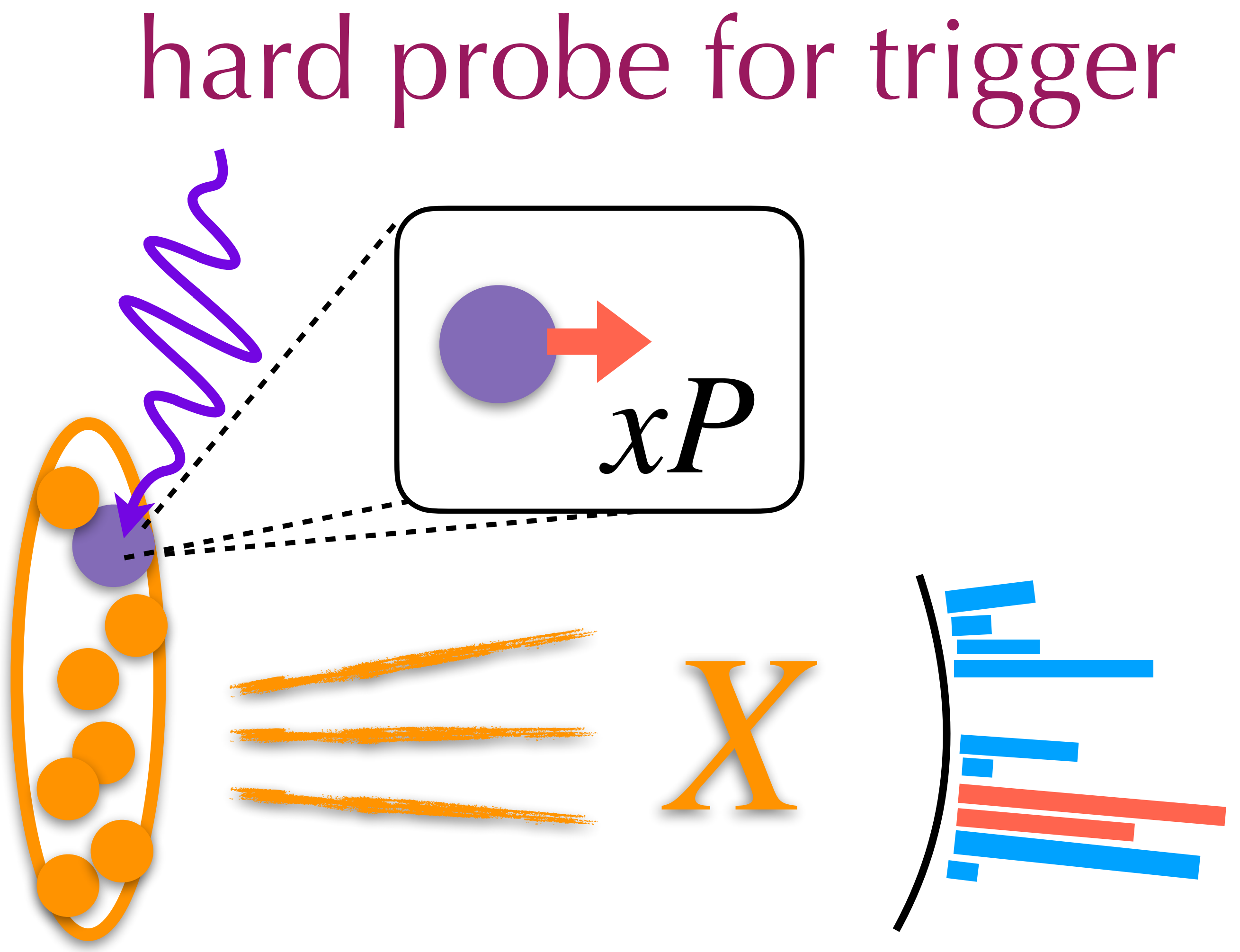
- Energy correlator in the forward region.
- Probe directly the broken proton
- Purely collinear object, insensitive to soft radiations, e.g. no Sudakov suppression
- Transverse dynamics through $\mathcal{E}(\theta)$
- Can be generalized to multiple-point correlation

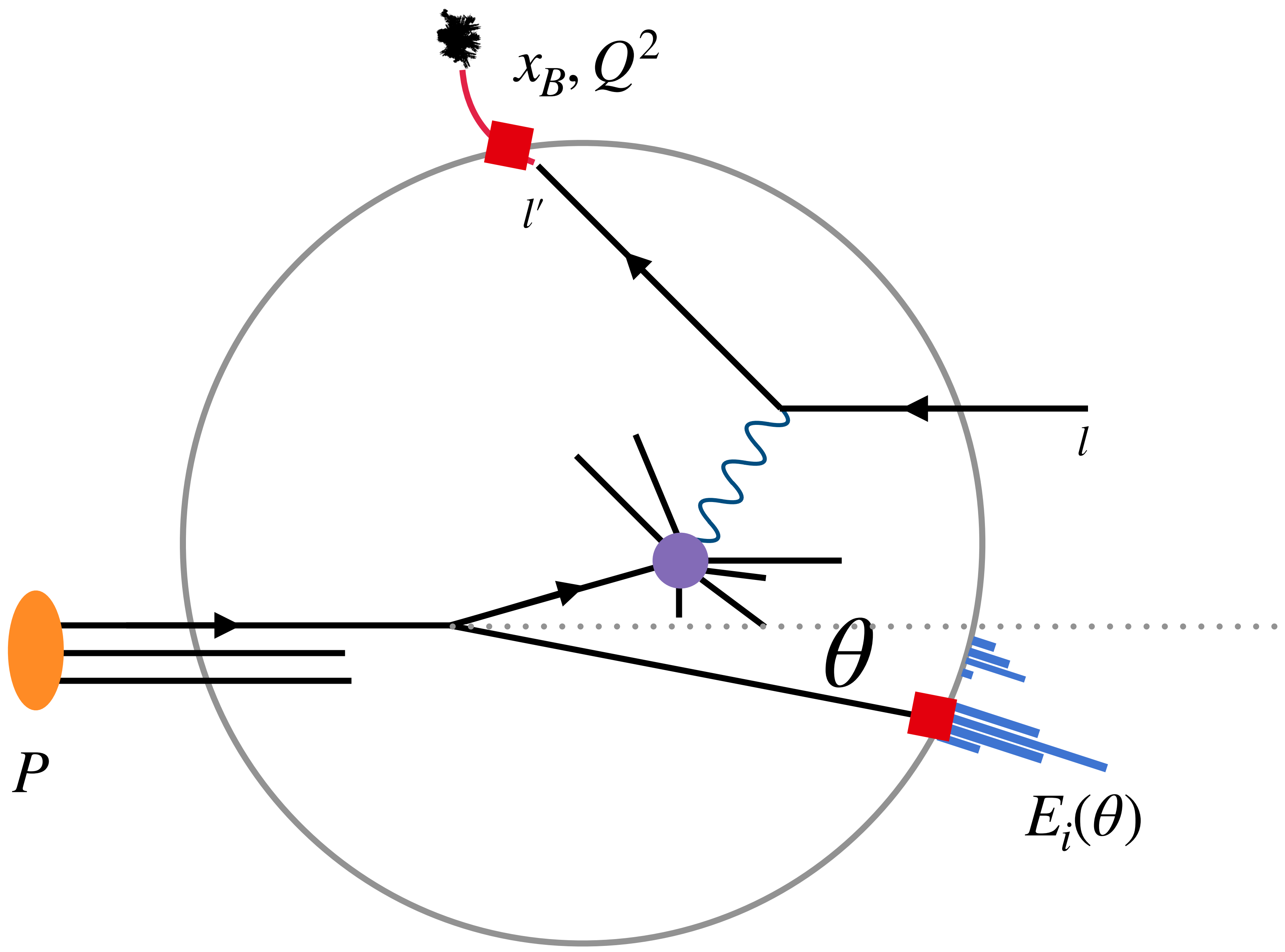
Measurement, Factorization and Properties

Nucleon EEC

XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9

- $\Sigma_N(Q^2,\theta) = \sum_i \int dx_B x_B^{N-1} \frac{E_i}{E_P} d\sigma(x_B, Q^2, p_i)\Theta(\theta - \theta_i)$





- Measurement in DIS
  - Full inclusive measurement, no jet/hadrons, weighted by E_i
  - Different θ's probe different physics

Measurement, Factorization and Properties

Nucleon EEC XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9

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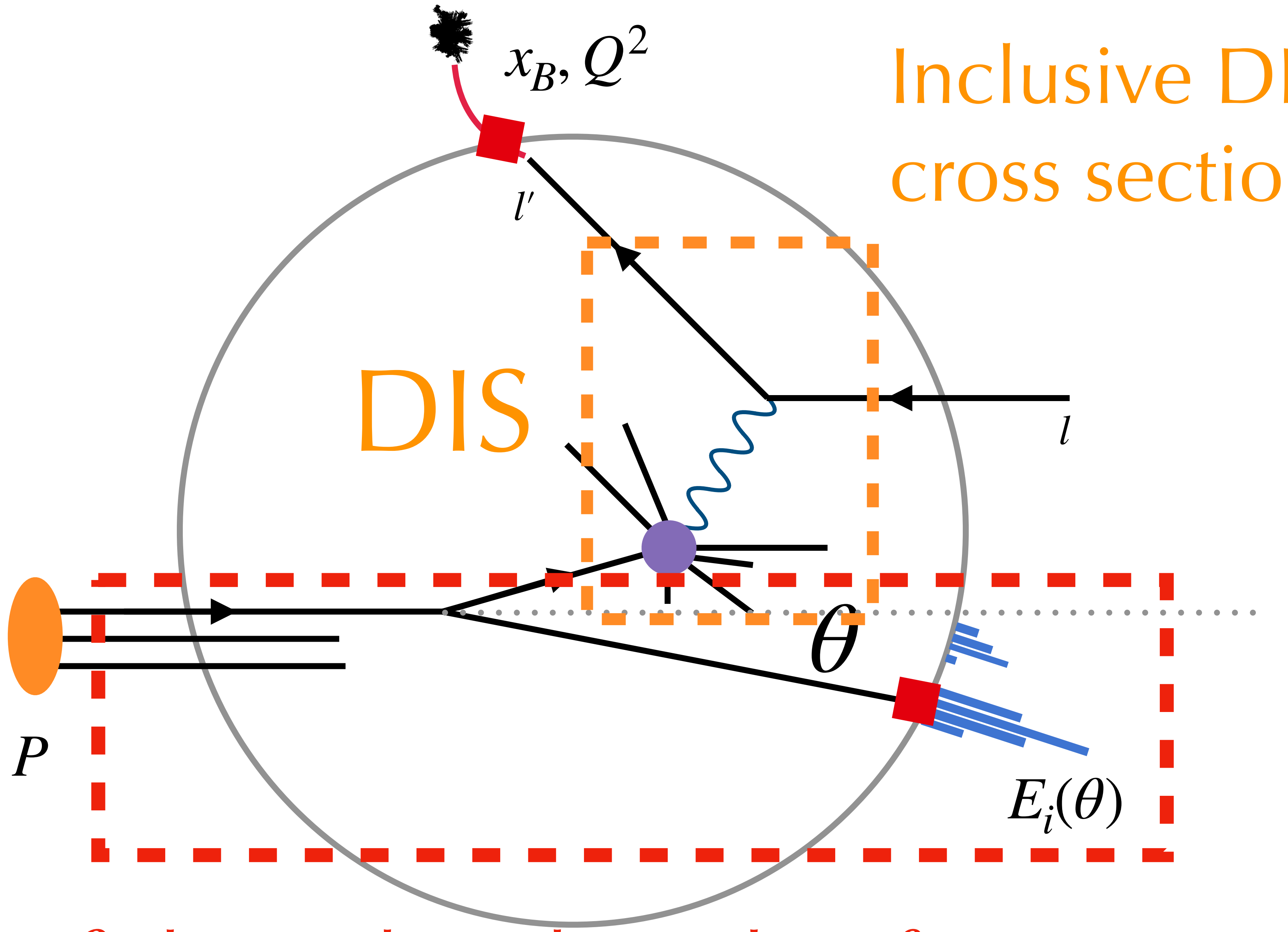

Inclusive DIS partonic cross section

θ shape directly probes f_{EEC}

- When $\theta Q \ll Q$, DIS type factorization

  $$\Sigma_N(Q^2,\theta) = \int u^{N-1} \hat{\sigma}\left(u, Q^2, \mu\right) f_{\text{EEC}}(N, \ln \frac{\theta Q}{u\mu})$$

  - Derived by SCET Cao, XL, Zhu, 2303.01530
  - rigorous QCD derivation by relating to the fracture function through sum rules

    Chen, Ma, Tong, 2406.08559
  - Free of soft contribution

Measurement, Factorization and Properties

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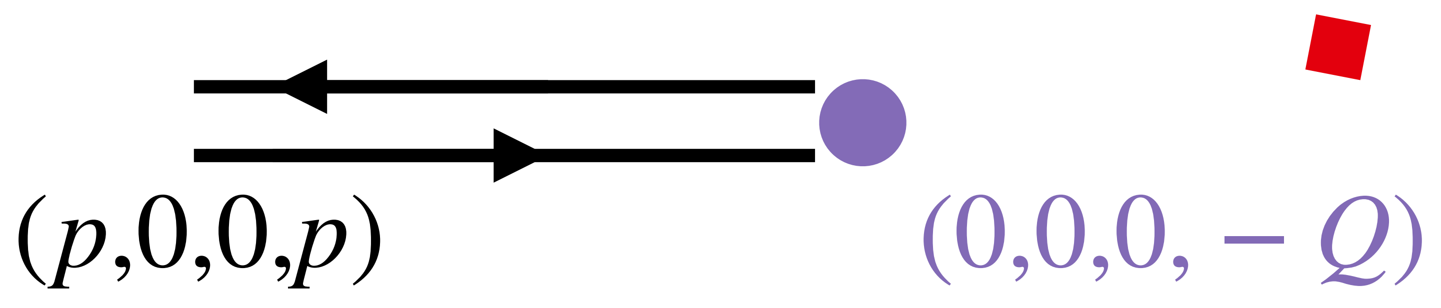
Breit Frame
LO



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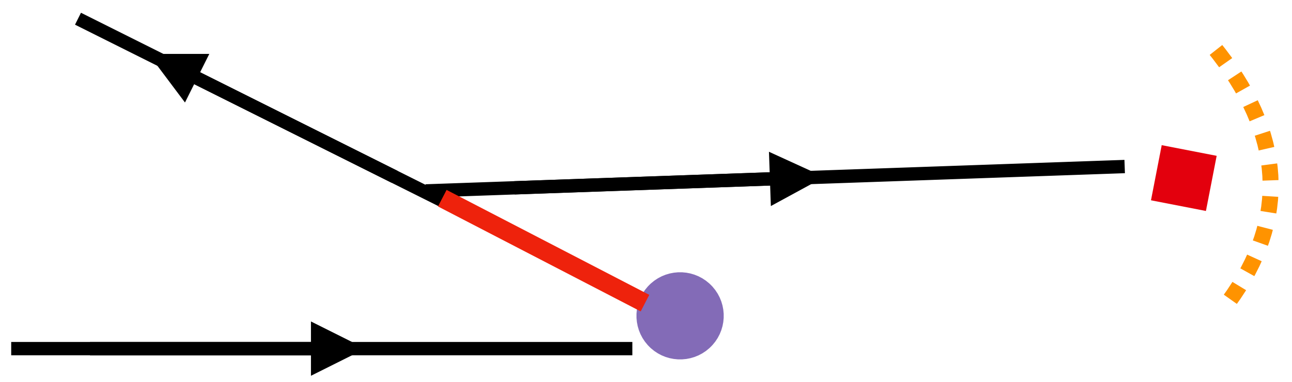
- $\Sigma_N(Q^2,\theta) = \sum_i \int dx_B x_B^{N-1} \frac{E_i}{E_P} d\sigma(x_B, Q^2, p_i)\Theta(\theta - \theta_i)$

Breit Frame
NLO



$\sim \frac{1}{Q^2} \times Q^2\theta^2 \to 0$

- When $\theta Q \ll Q$, DIS type factorization

$$\Sigma_N(Q^2,\theta) = \int u^{N-1} \hat{\sigma}\left(u, Q^2, \mu\right) f_{\mathrm{EEC}}(N, \ln \frac{\theta Q}{u\mu})$$

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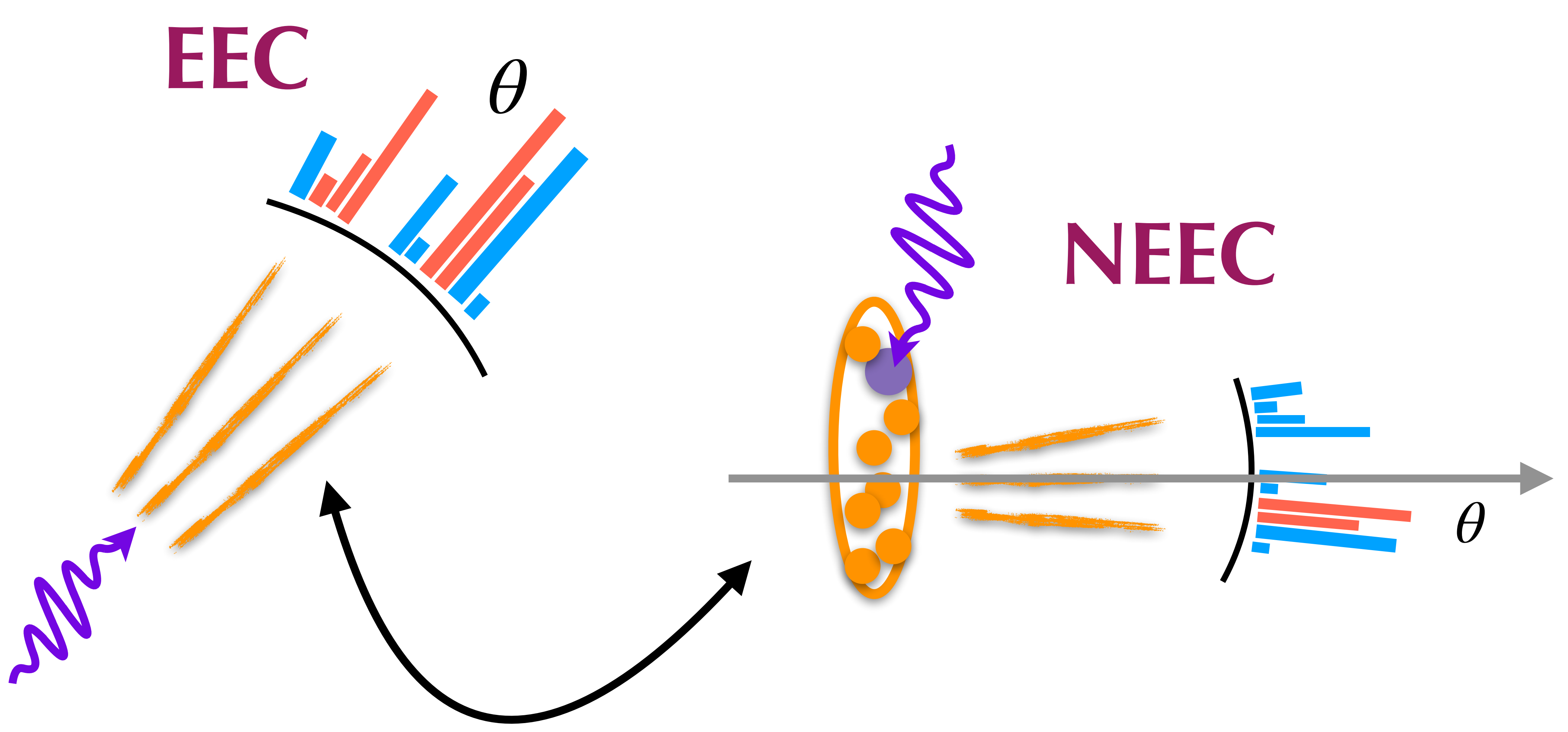


- When $\theta Q \ll Q$, DIS type factorization

$$\Sigma_N(Q^2, \theta) = \int u^{N-1} \hat{\sigma}\left(u, Q^2, \mu\right) f_{\mathrm{EEC}}(N, \ln \frac{\theta Q}{u\mu})$$

- Space like version of the EEC in e^+e^-

$$\Sigma = \int du u^2 \sigma(u, \mu) J(\mu, \ln \frac{\theta u Q}{\mu})$$

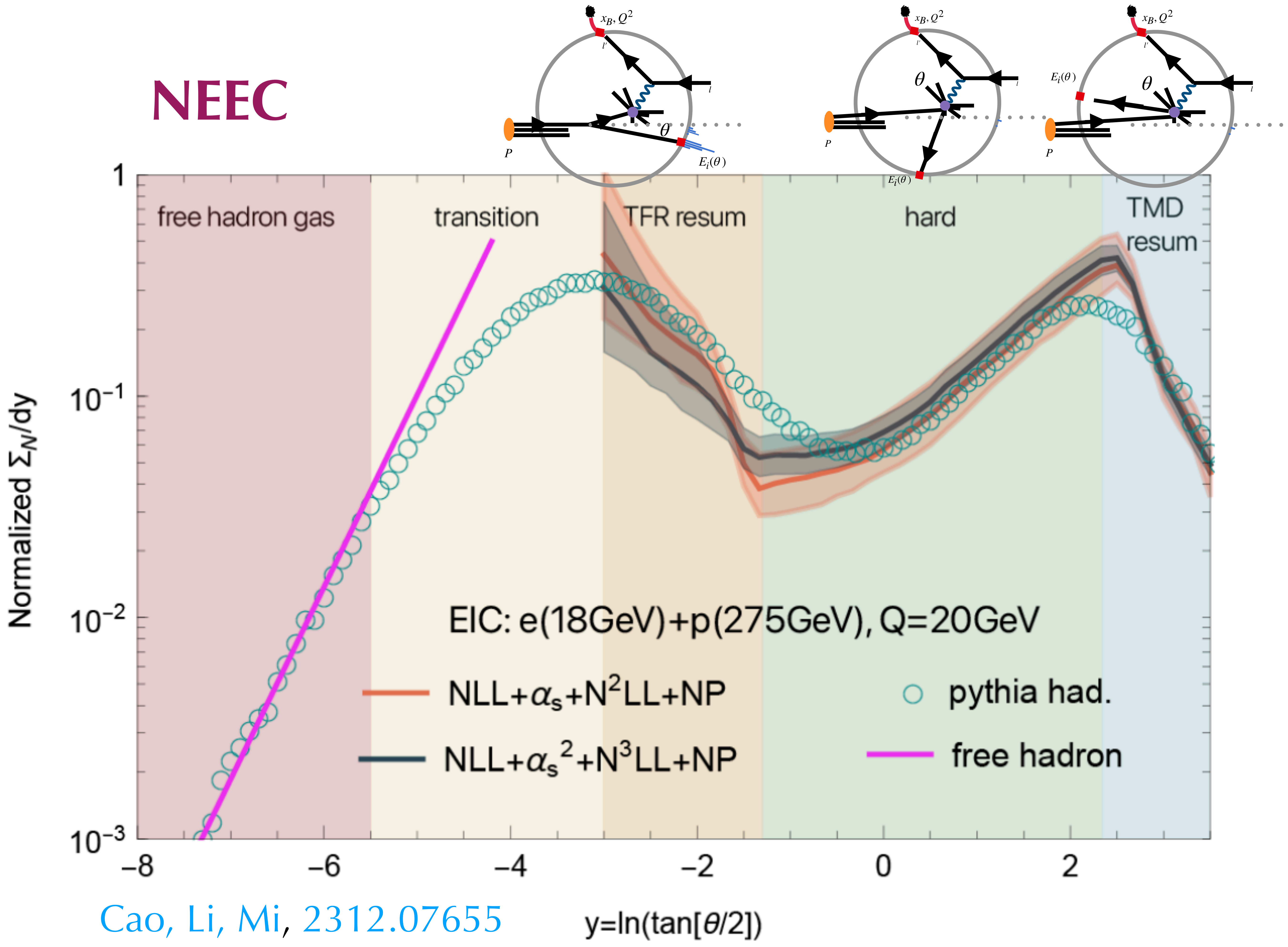
Dixon, Moult, Zhu, 2019

Chen, 2311.00350

Similar factorization form

Measurement, Factorization and Properties

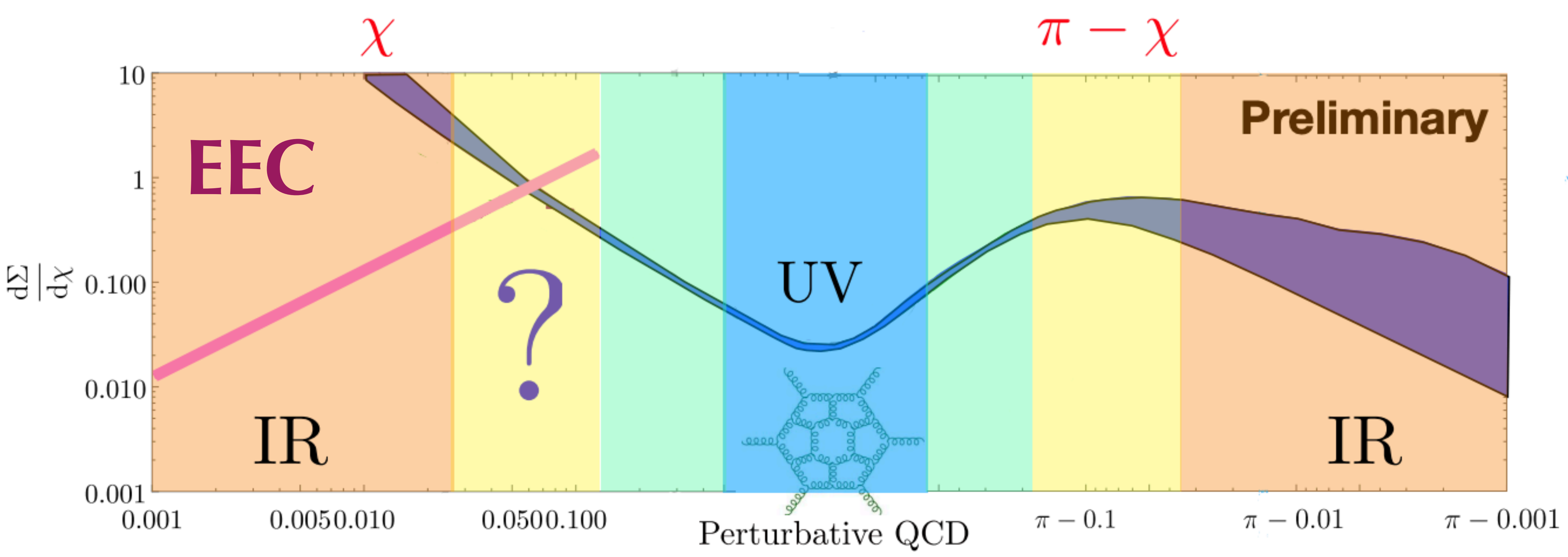
NEEC



Cao, Li, Mi, 2312.07655

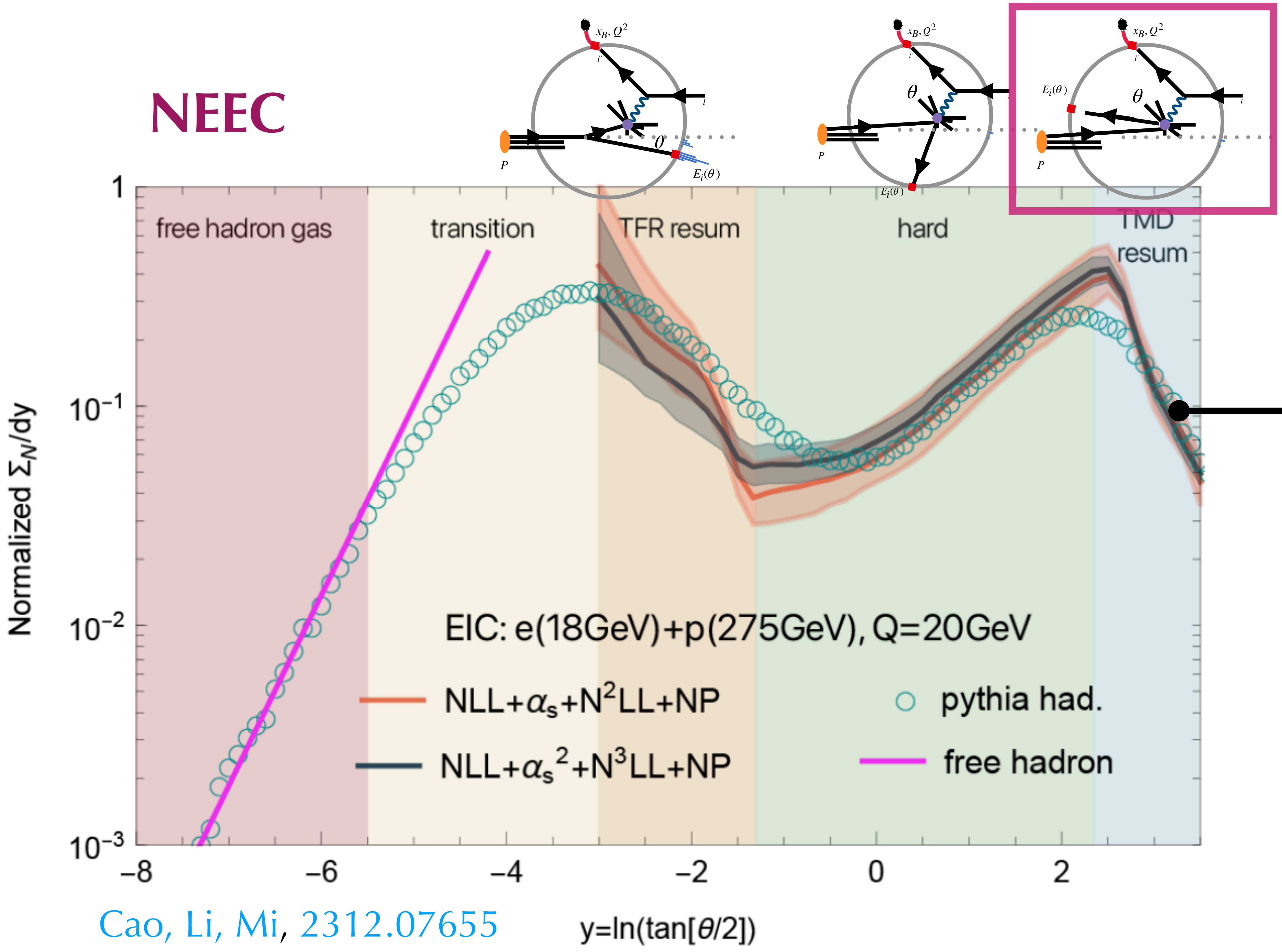
Share many similarities in the spectrum

EEC



Moult talk

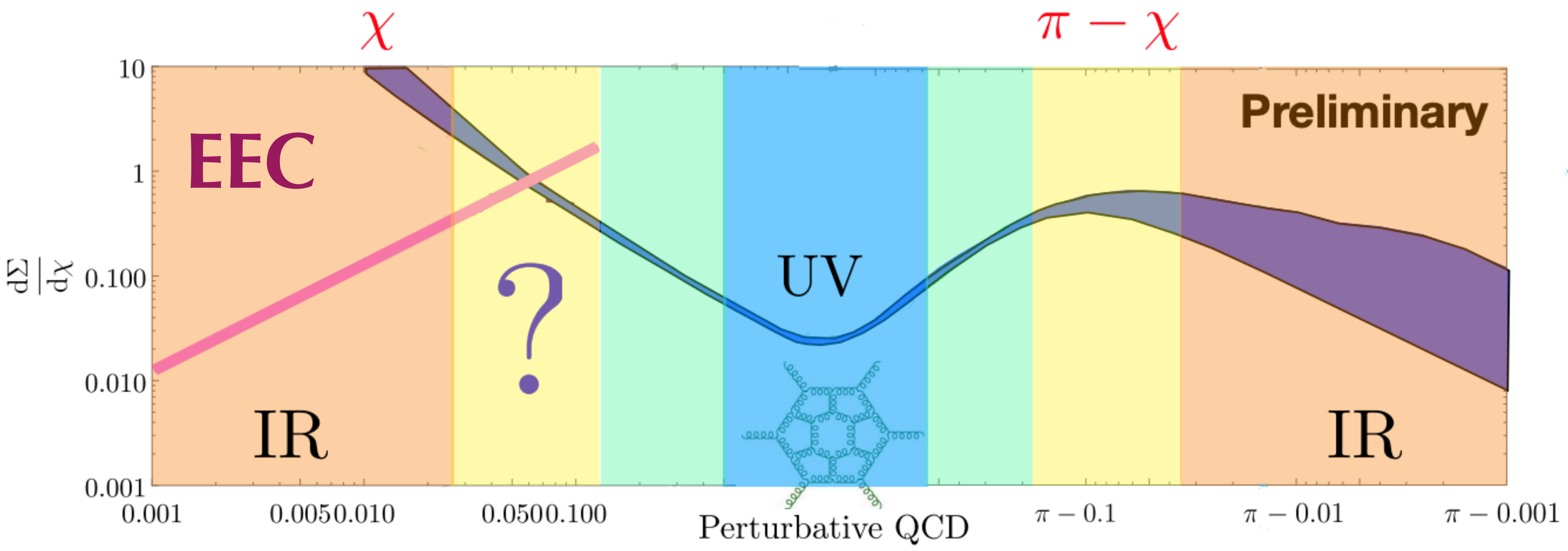
Measurement, Factorization and Properties



Cao, Li, Mi, 2312.07655

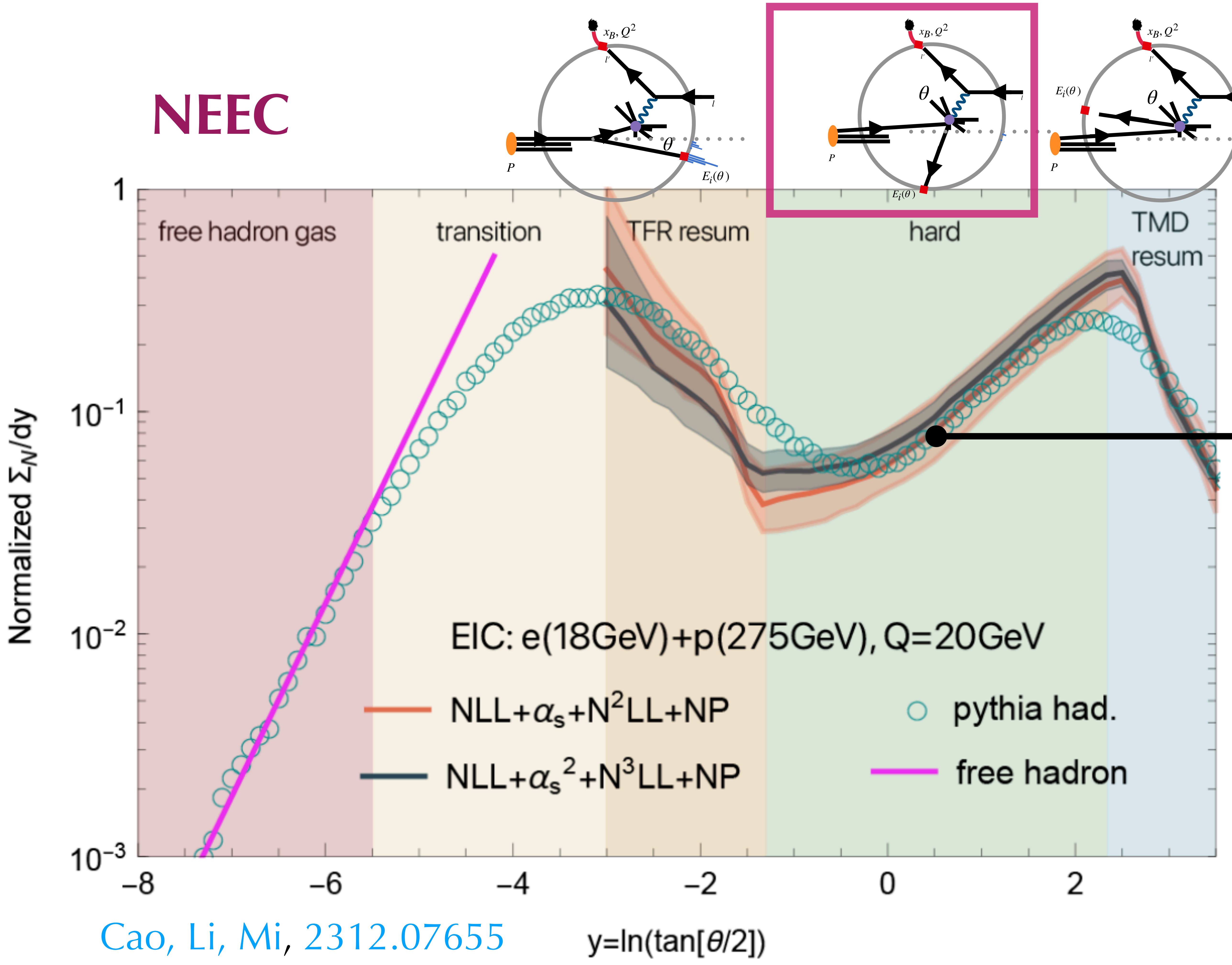
TMD region, $\theta \sim \pi$

- conventional TMD physics
- Peak driven by Pert. Sudakov



Moult talk

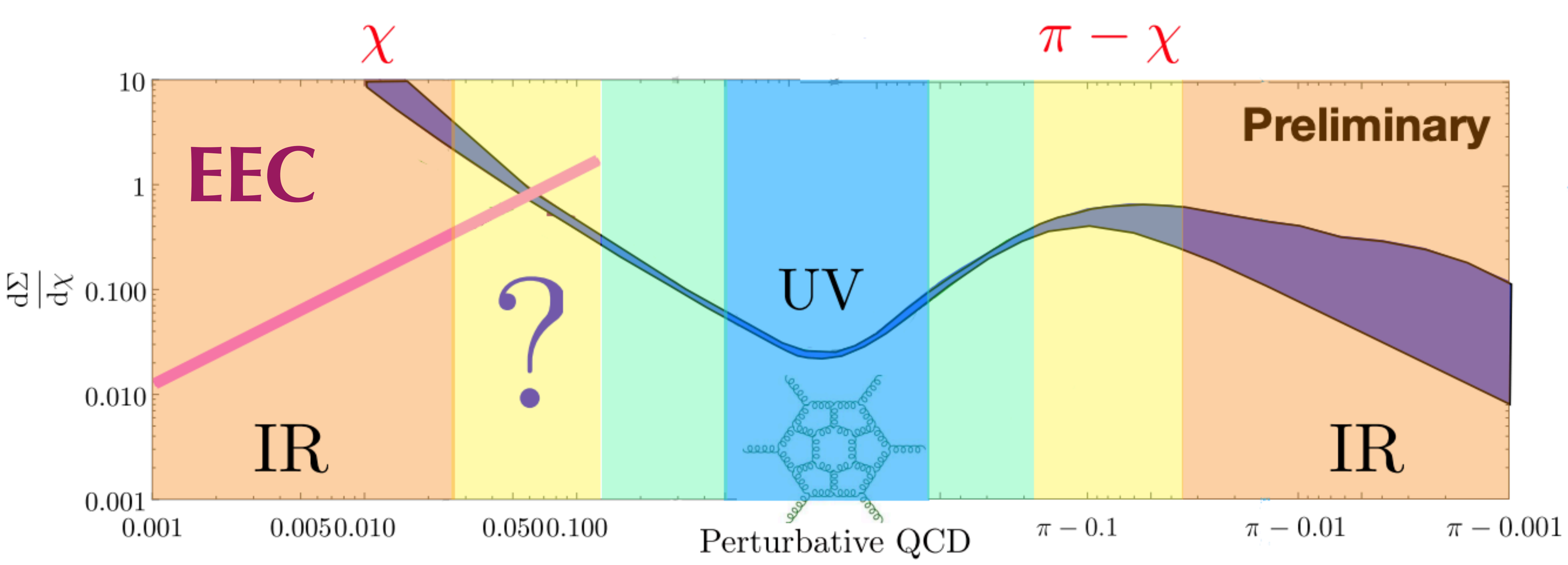
Measurement, Factorization and Properties



Cao, Li, Mi, 2312.07655

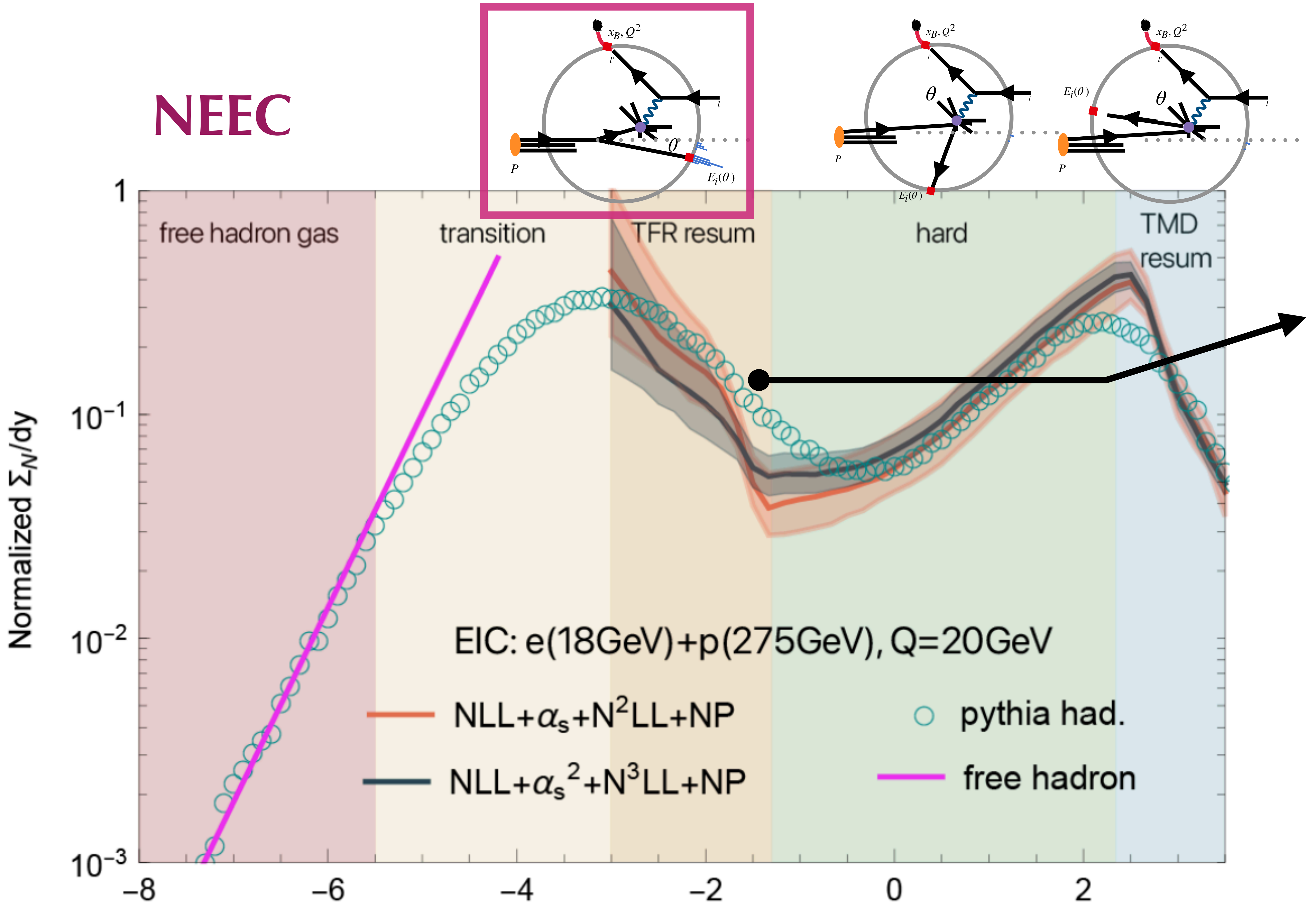
Hard region, $\theta \sim 1$

- Fixed-order does the job



Moult talk

Measurement, Factorization and Properties



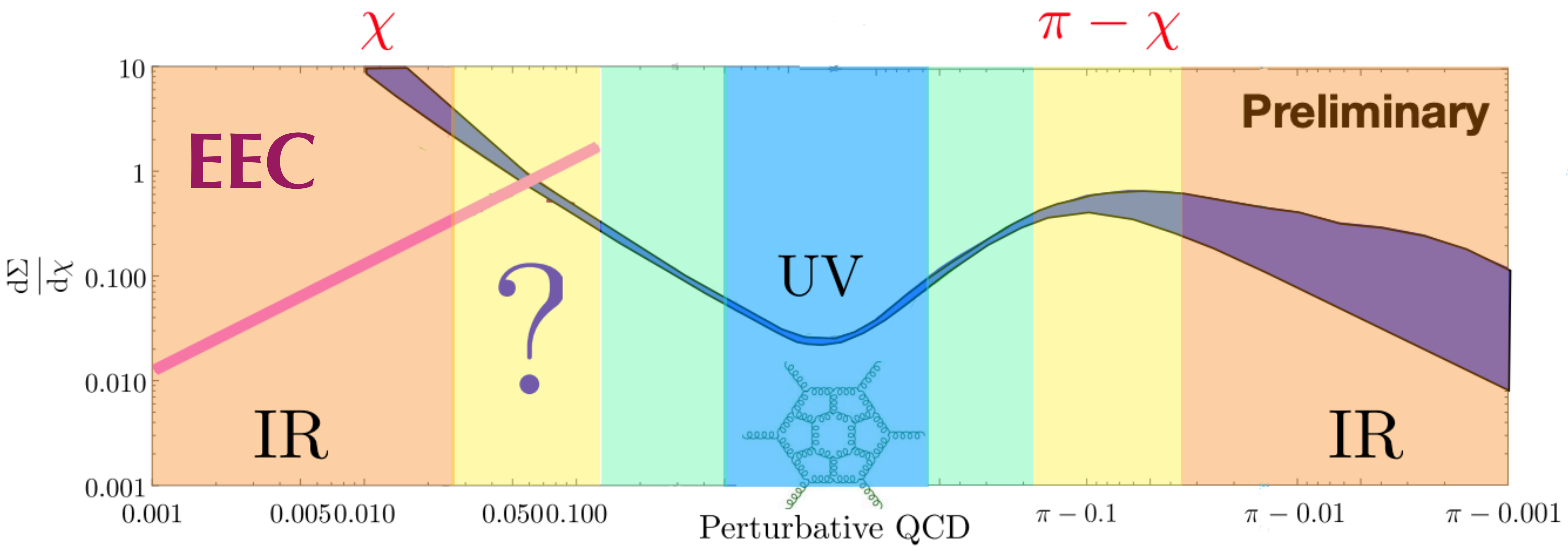
Cao, Li, Mi, 2312.07655

$\Lambda_{\rm QCD} \ll \theta Q \ll Q$

- Perturbatively calculable

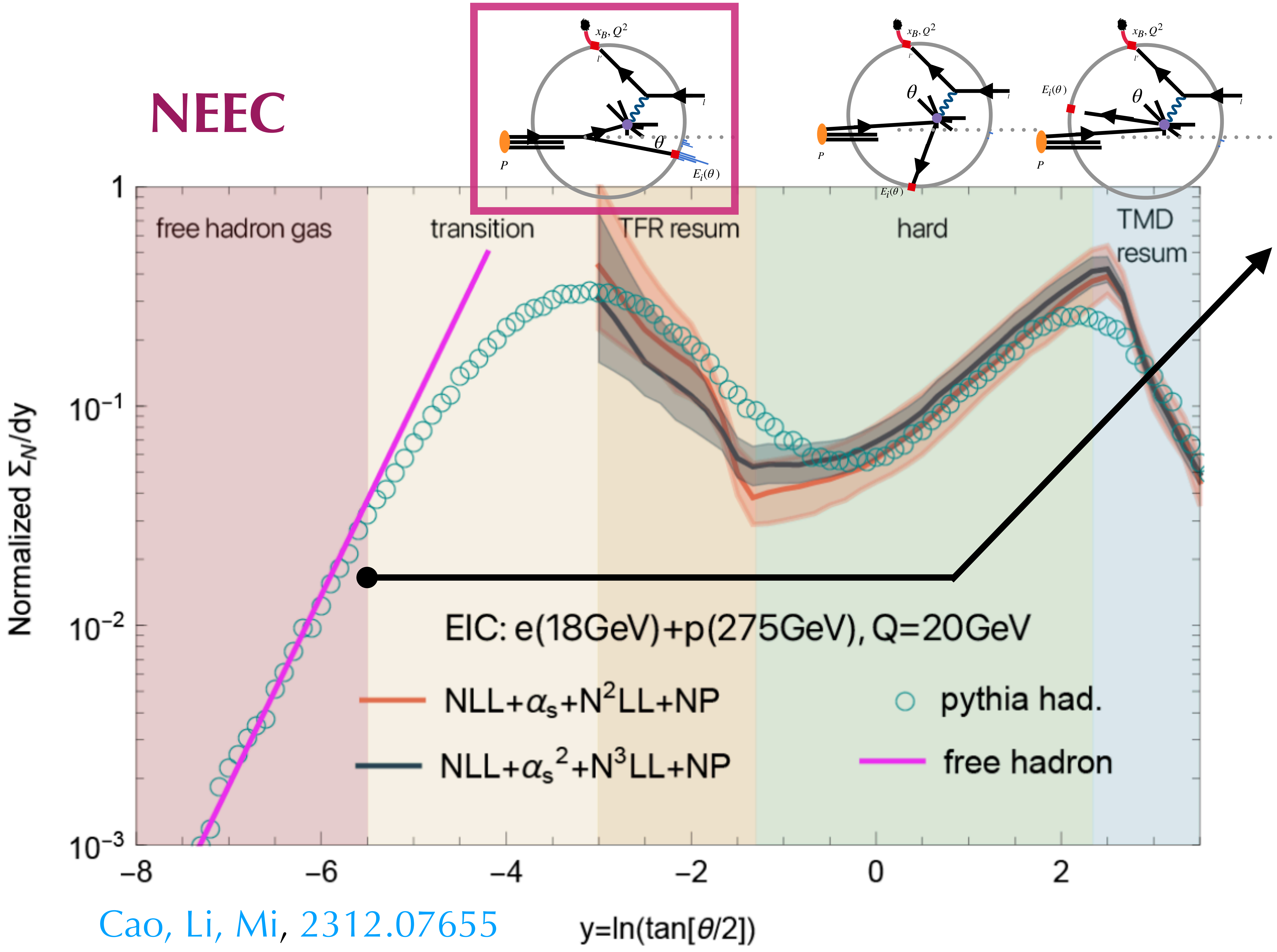
$$f^{(0)}_{\rm EEC}(\theta) \propto \left[\frac{1}{\theta^2}(1-x)P(x)\right] \times [\xi f(\xi)]$$

- Dynamics dominated by coll. splitting
- Power law: $\theta^{-2+\gamma}$, γ by $P(N)$ + coll. PDF



Moult talk

Measurement, Factorization and Properties

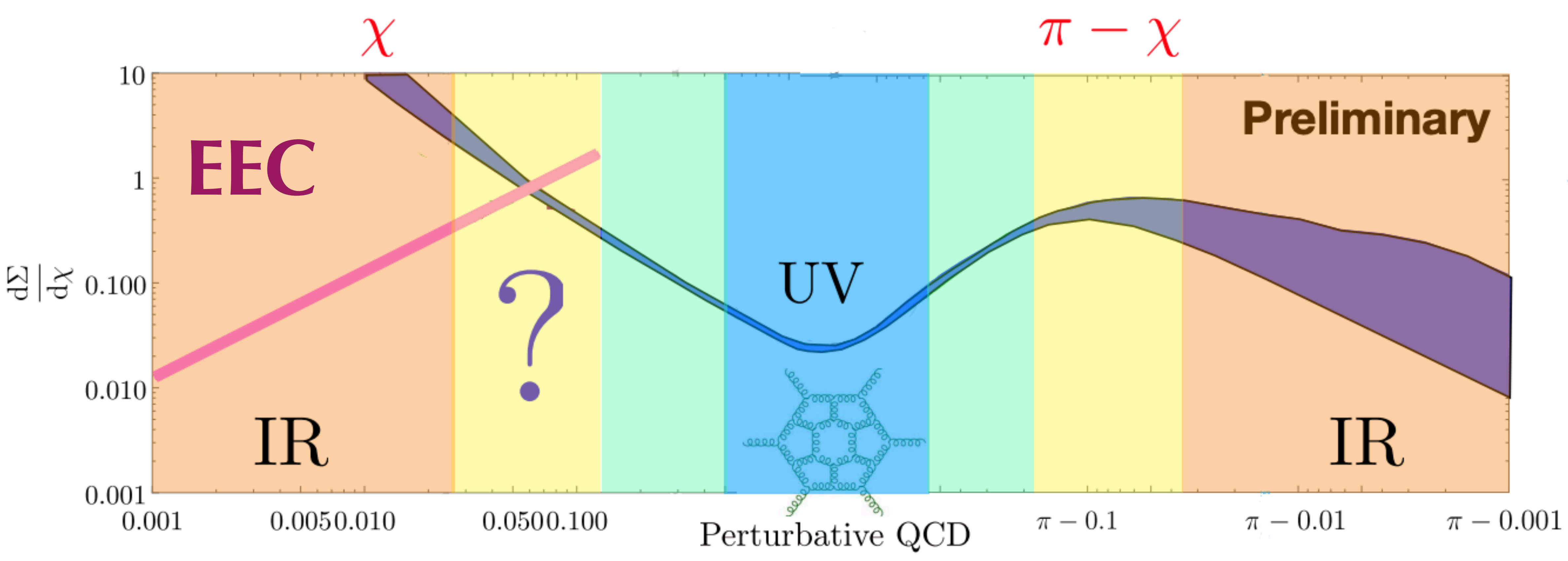


Cao, Li, Mi, 2312.07655

Deep NP region

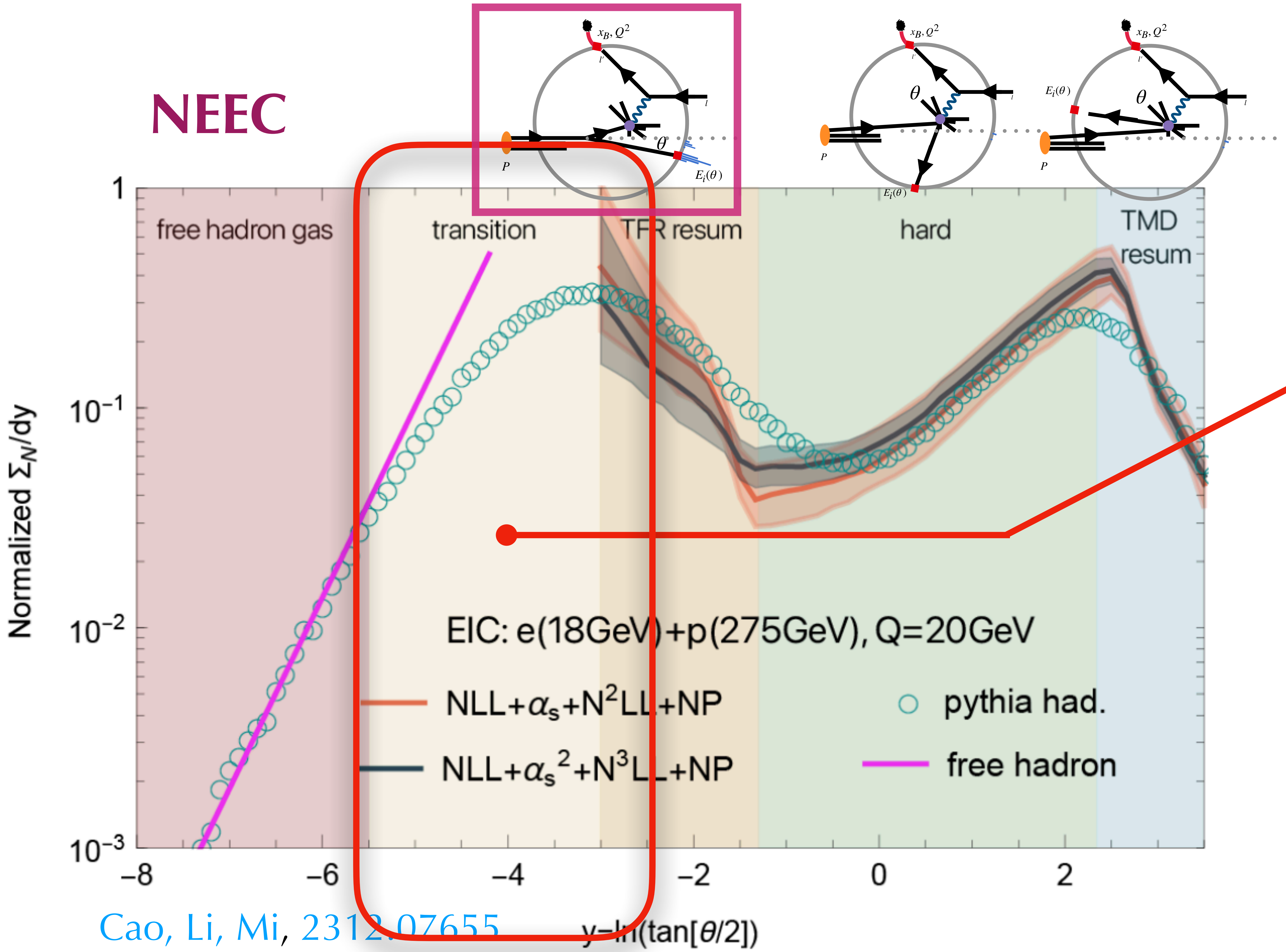
- Un-correlated distribution

$$d\Sigma/d\theta \sim \theta$$



Moult talk

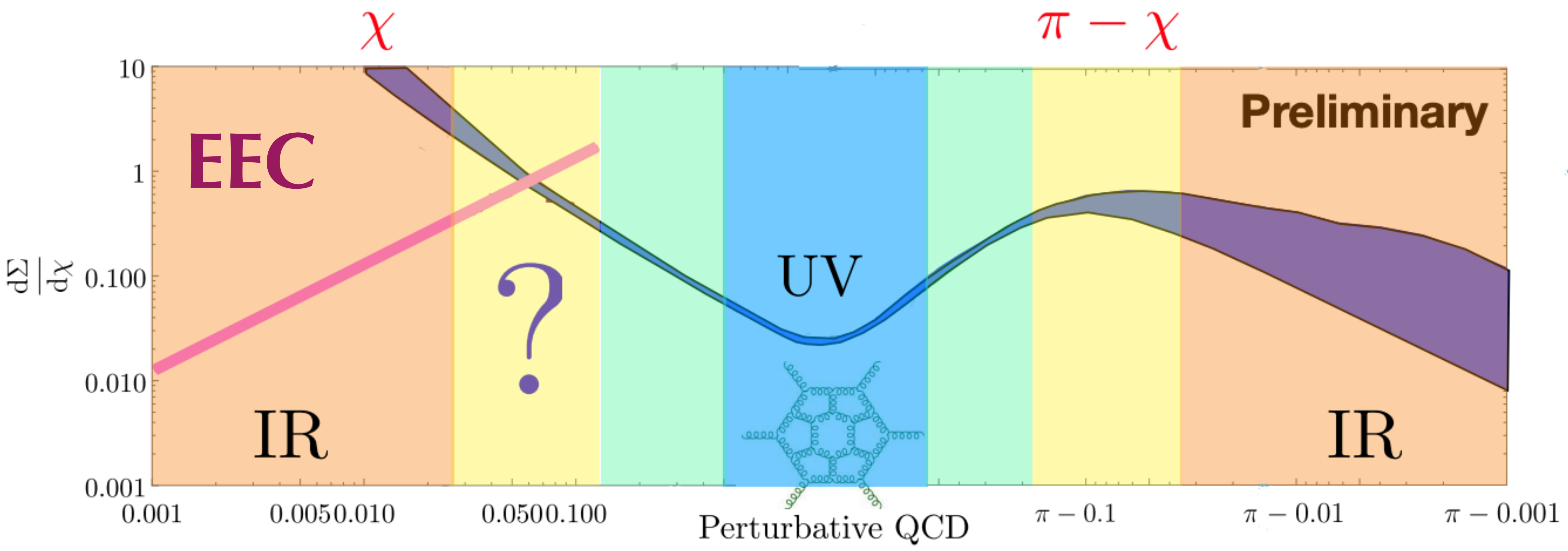
Measurement, Factorization and Properties



Cao, Li, Mi, 2312.07655

NP region

- Enhanced NP region, vs. TMD
- To be determined by future measurements
- Encodes info. on proton intrinsic structure and NP dynamics

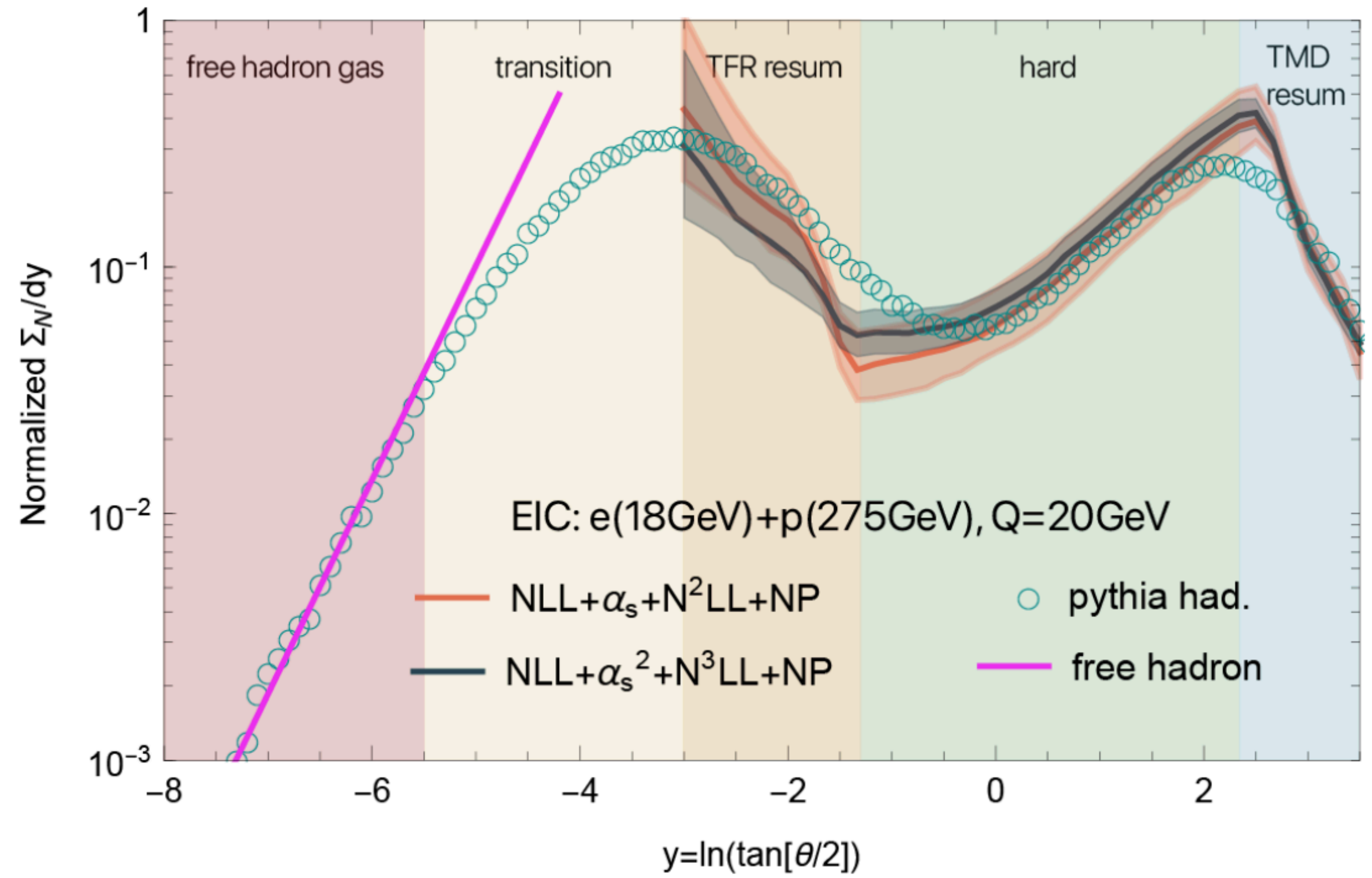


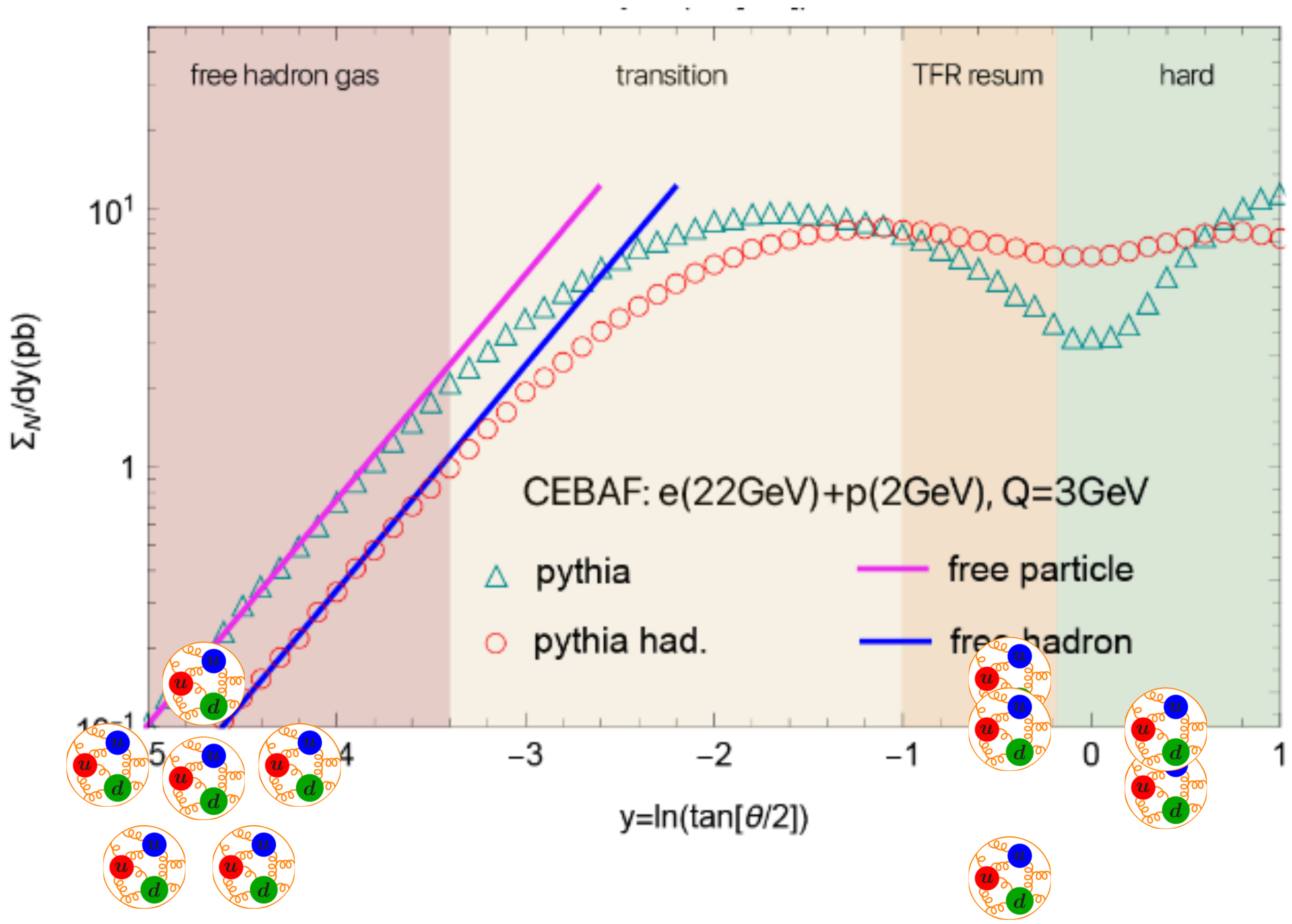
Moult talk

Phenomenology

NEC as a generating observable

XL, Zhu, **arxiv: 2403.08874**
XL, Shao, Zhu, **in preparation**





- It will be nice if experiments can confirm the framework.
- Not that forward to probe the scaling rule region and the onset of the transition region, $y \lesssim 2.5$, for $Q \lesssim 10\,\mathrm{GeV}$@HERA, CEBAF@JLab maybe perfect for the deep NP region
- Possible precision measurement of TMD in the b-to-b region

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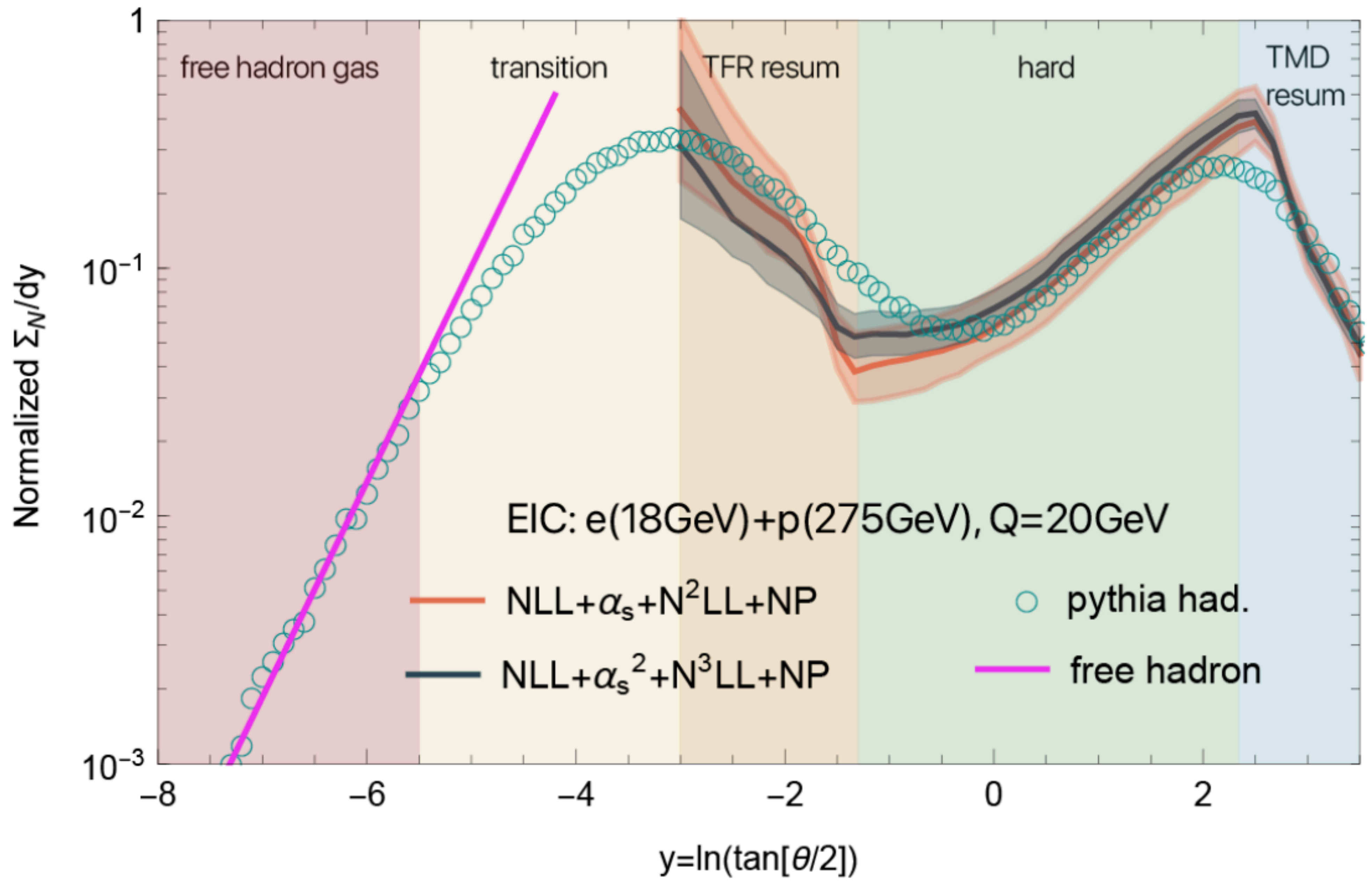

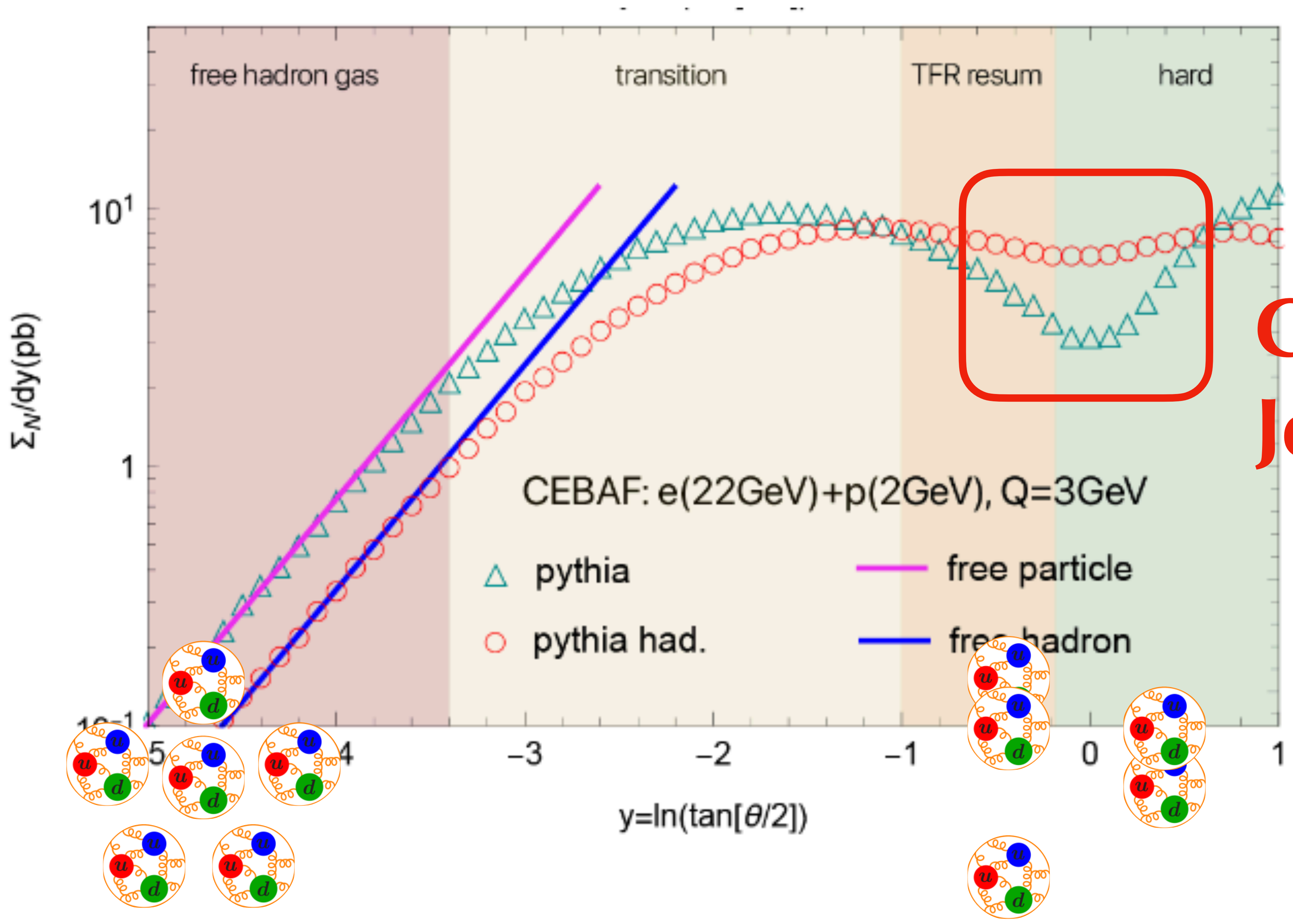

Can we see Jet?!

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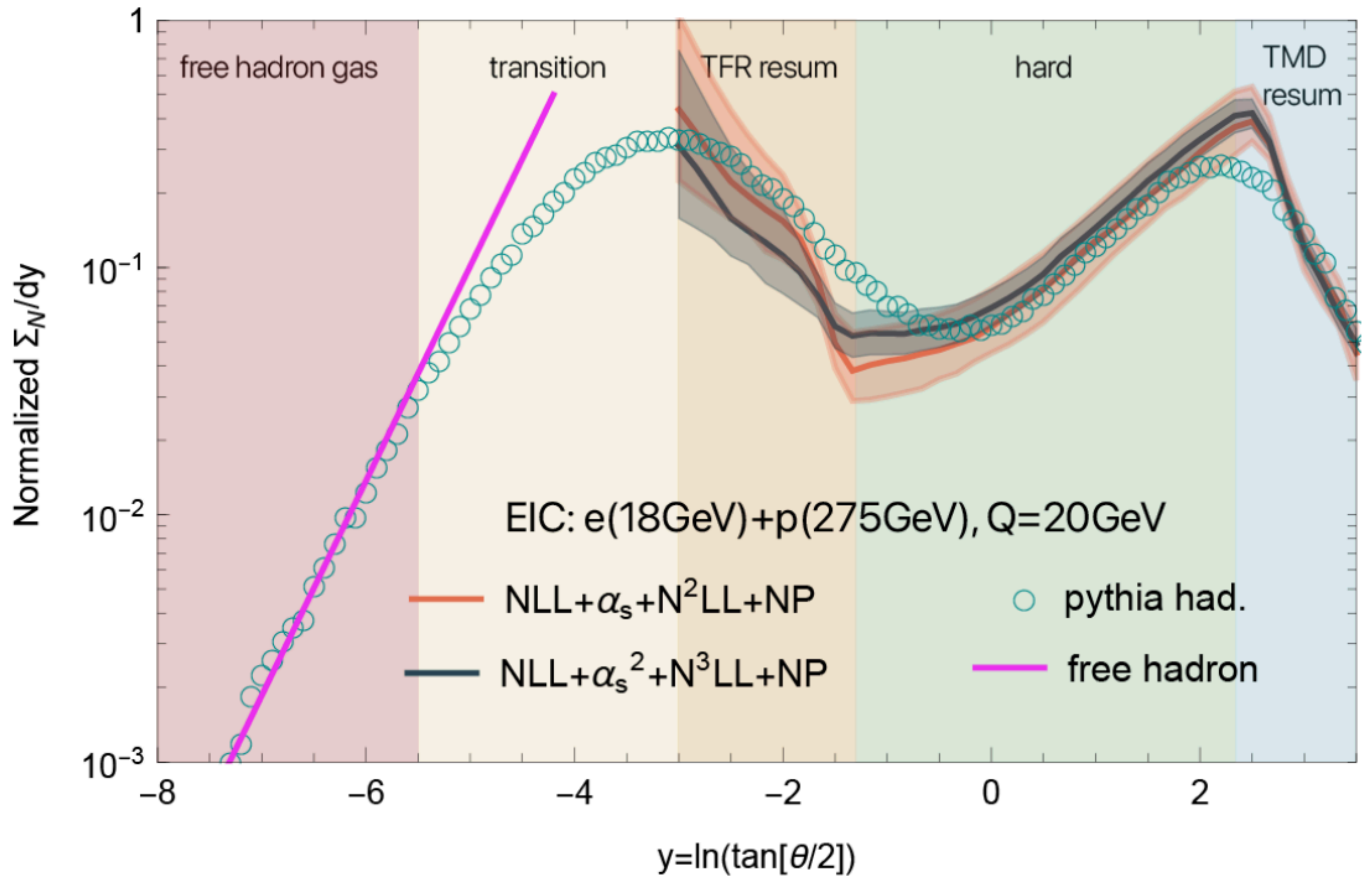

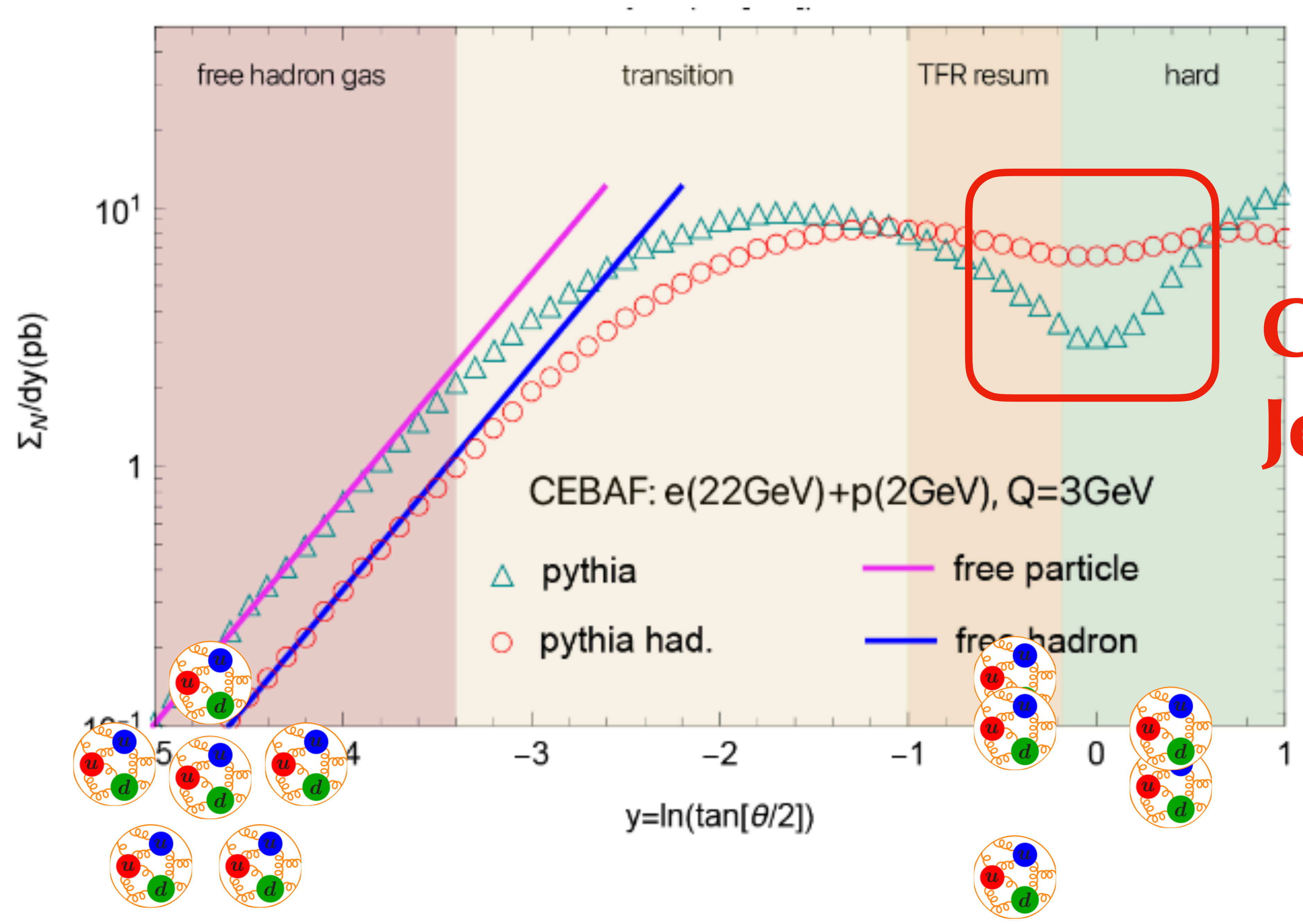

Can we see Jet?!

- The small θ region and TMD region can be related

NEC as a generating observable

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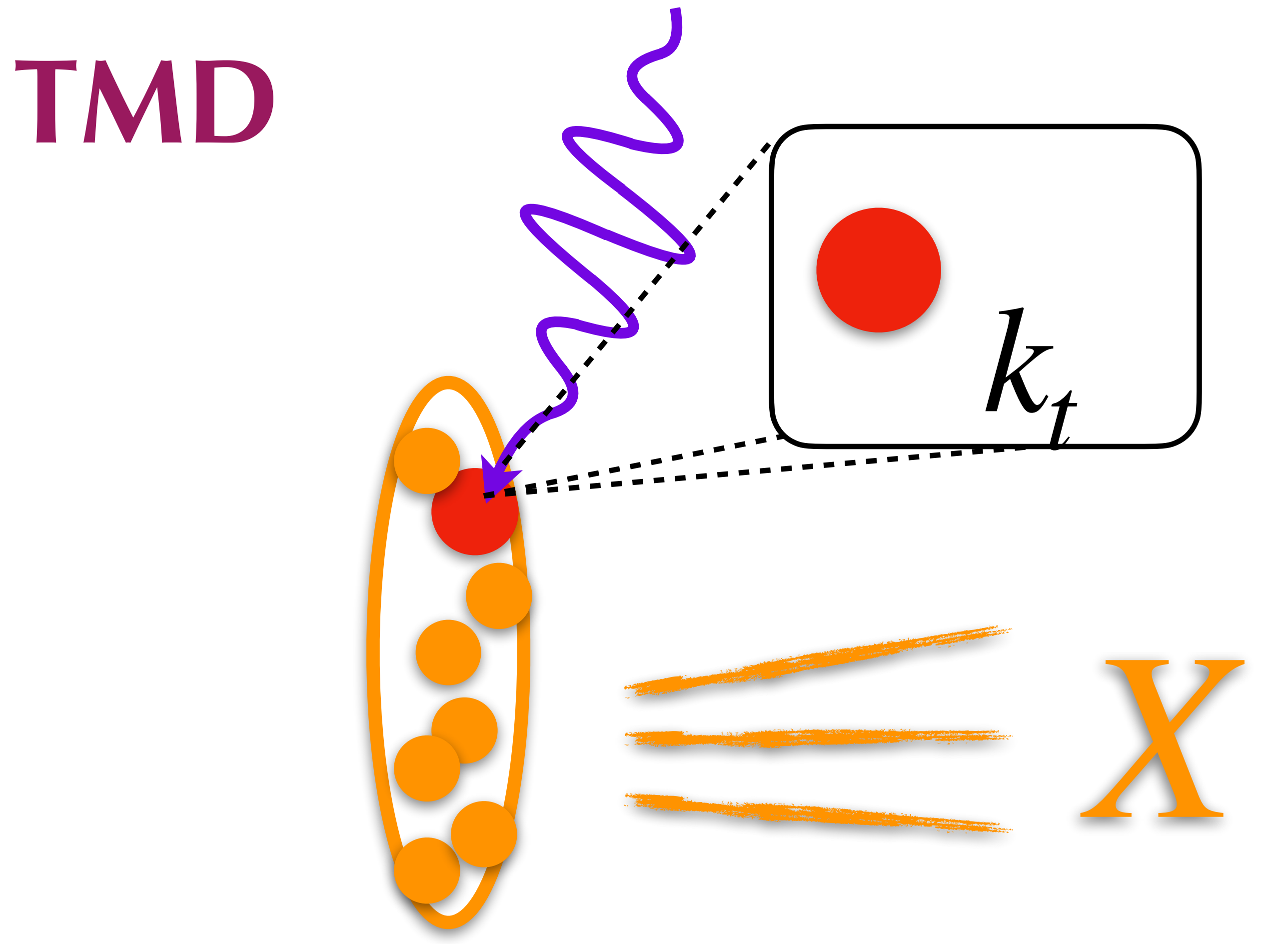

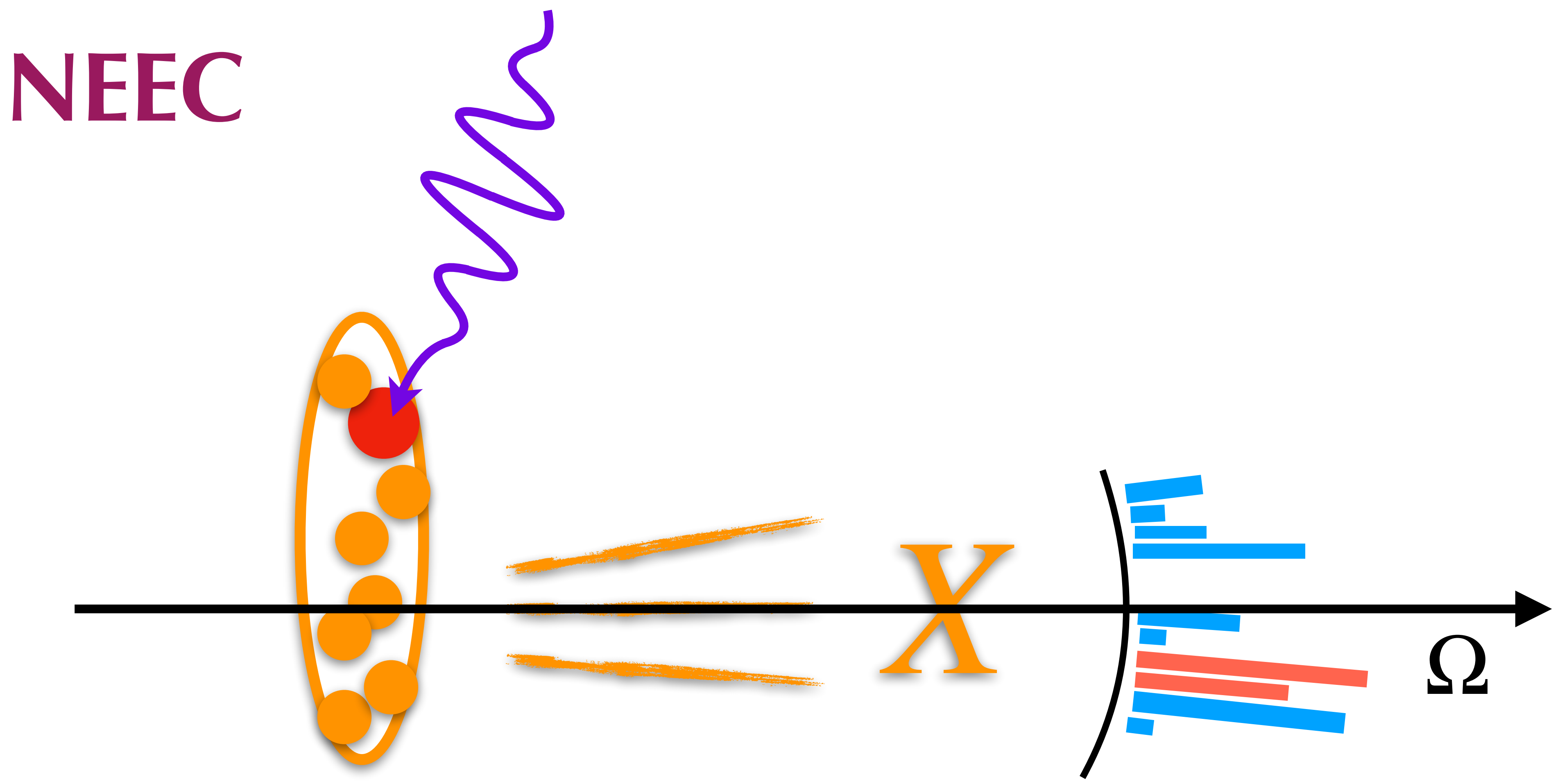

$$\vec{k}_t = -\sum_{i \in X} \vec{p}_{i,t} = -\sum_{i \in X} E_i \sin\theta_i (\cos\phi_i, \sin\phi_i)$$

$$\mathscr{E}(\Omega) = \sum_{i \in X} E_i \delta(\Omega - \Omega_i)$$

NEC as a generating observable

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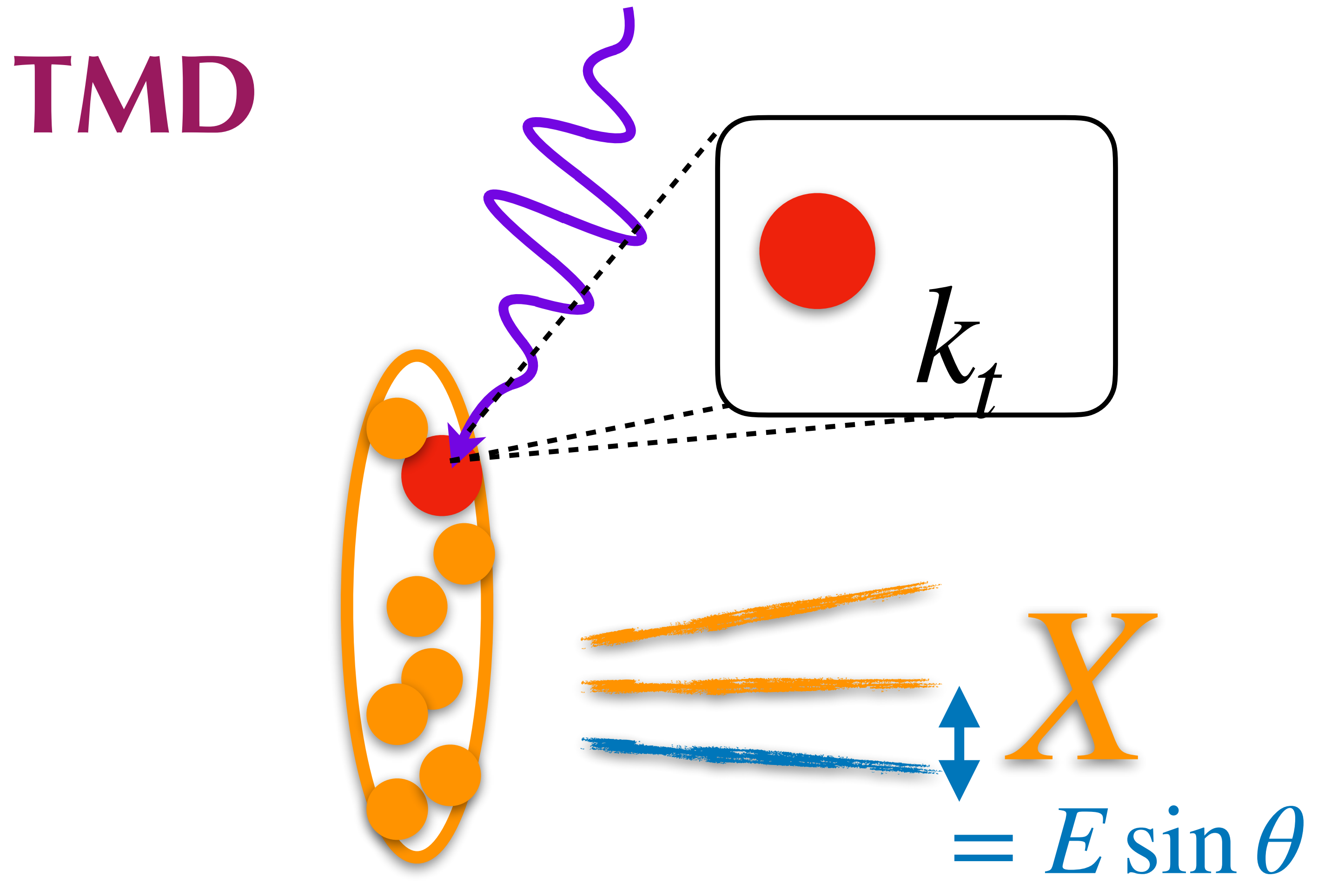

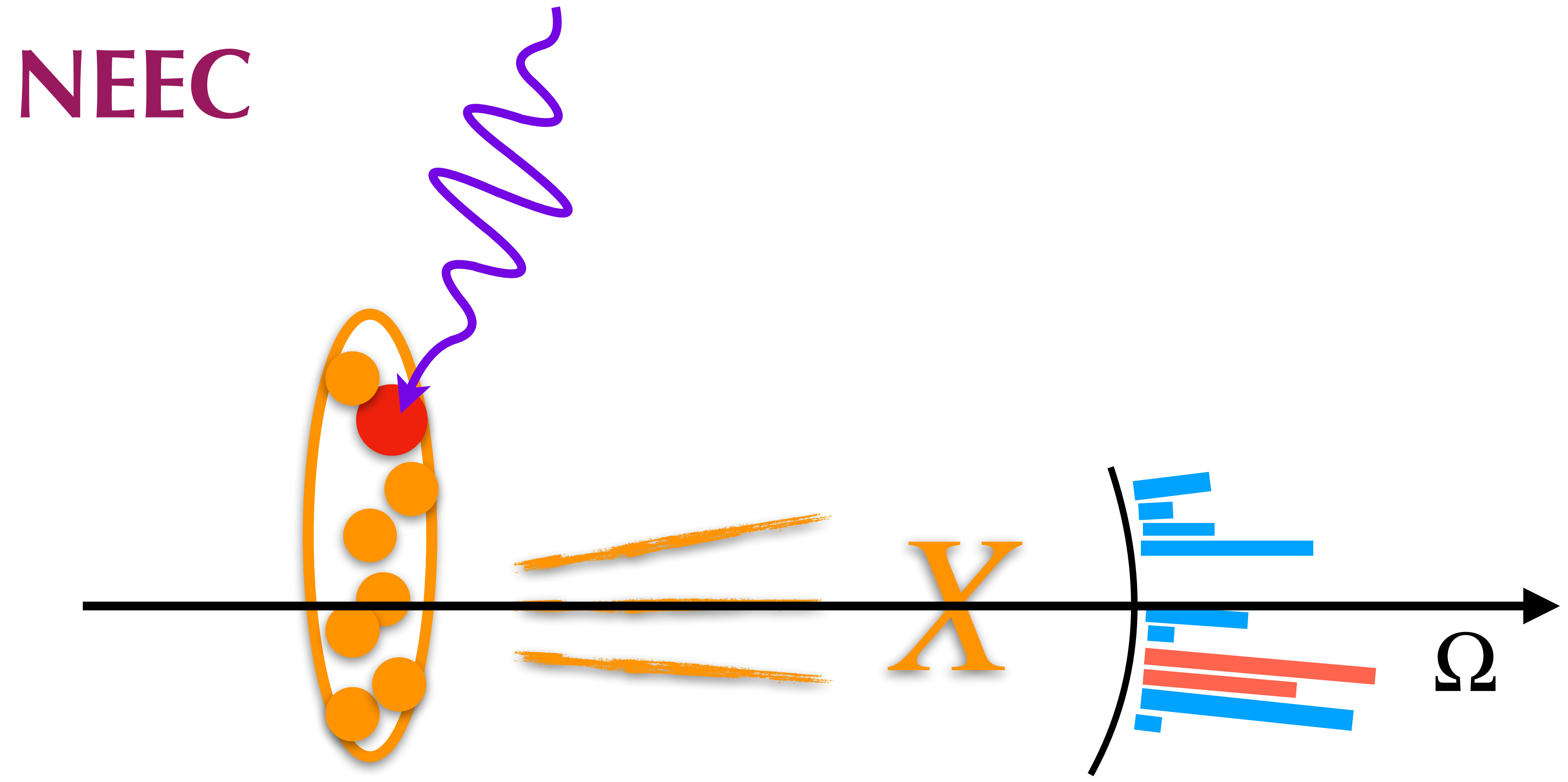

$$\vec{k}_t = -\int d\theta d\phi \sum_i E\sin\theta(\cos\phi, \sin\phi)\delta(\Omega - \Omega_i)$$
$$= -\int d\theta d\phi \, \sin\theta(\cos\phi, \sin\phi)\, \mathcal{E}(\Omega)$$

$$\mathcal{E}(\Omega) = \sum_{i\in X} E_i \delta(\Omega - \Omega_i)$$

$$\int^{\mu} dk_t k_t^n f(k_t) = (-)^n \int^R \prod_n d\Omega\, w(\Omega_1)\ldots w(\Omega_n)\langle P| \ldots \mathcal{E}(\Omega_1)\ldots\mathcal{E}(\Omega_n)\ldots |P\rangle$$

For TMD TMM see e.g.: del Rio, Prokudin, Scimemi, Vladimirov, arXiv:2402.01836v1

NEC as a generating observable

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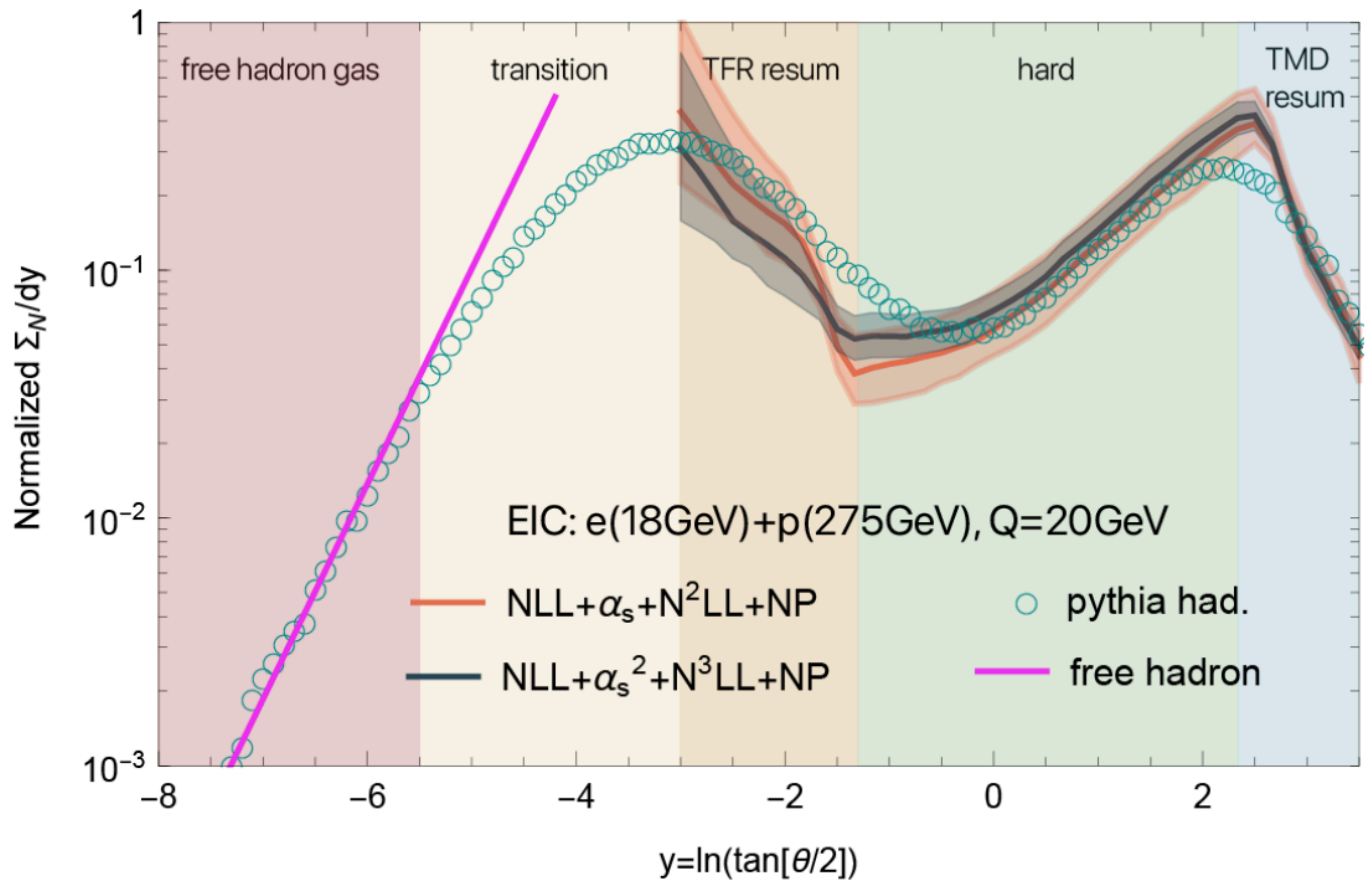
$$\int dk_t k_t^n f(k_t) = (-)^n \int \prod_n d\Omega\, w(\Omega_1)\ldots w(\Omega_n) \langle P | \ldots \mathscr{E}(\Omega_1)\ldots\mathscr{E}(\Omega_n)\ldots | P\rangle$$

- TMD PDFs (moment) can be obtained by measuring N-pt Nucleon Energy Correlator, by suitably selecting $w(\Omega)$
- Inclusive measurement! Do not force b-to-b limit, no jets/fragmentation function involved.
- Nucleon Energy Correlator can be regarded as a generating observable, contains more comprehensive information

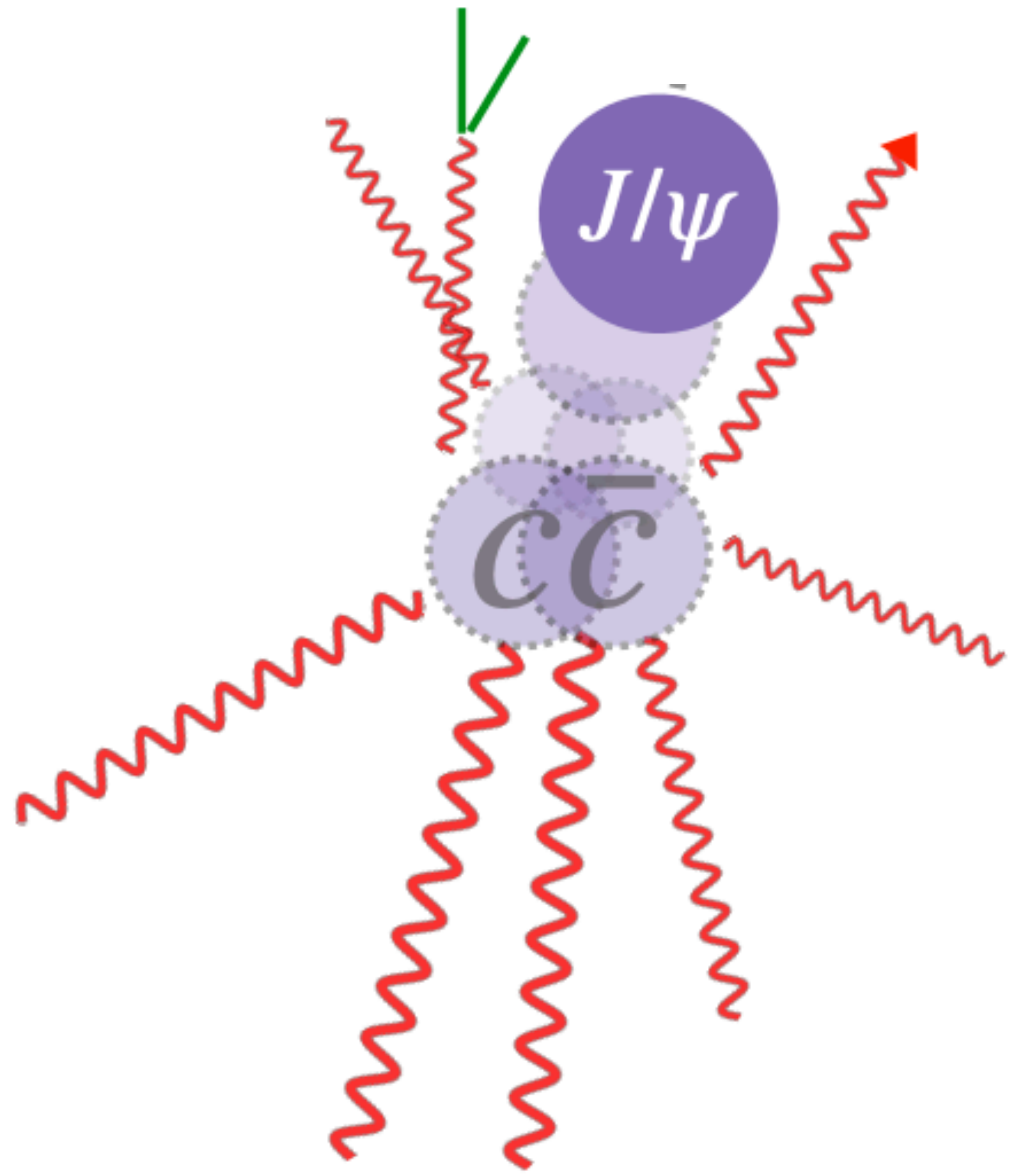


Quarkonium Energy Correlator

Motivation

Quarkonium Physics

- regarded as an excellent place to study non-pert phenomenon for a long time
- How $c\bar{c} \to J/\psi$?
  - NRQCD: encoded in $\langle \mathcal{O}_{\mathbf{1}} \rangle, \langle \mathcal{O}_{\mathbf{8}} \rangle$
  - remains largely unknown: amount of energy released? Energy Distribution?



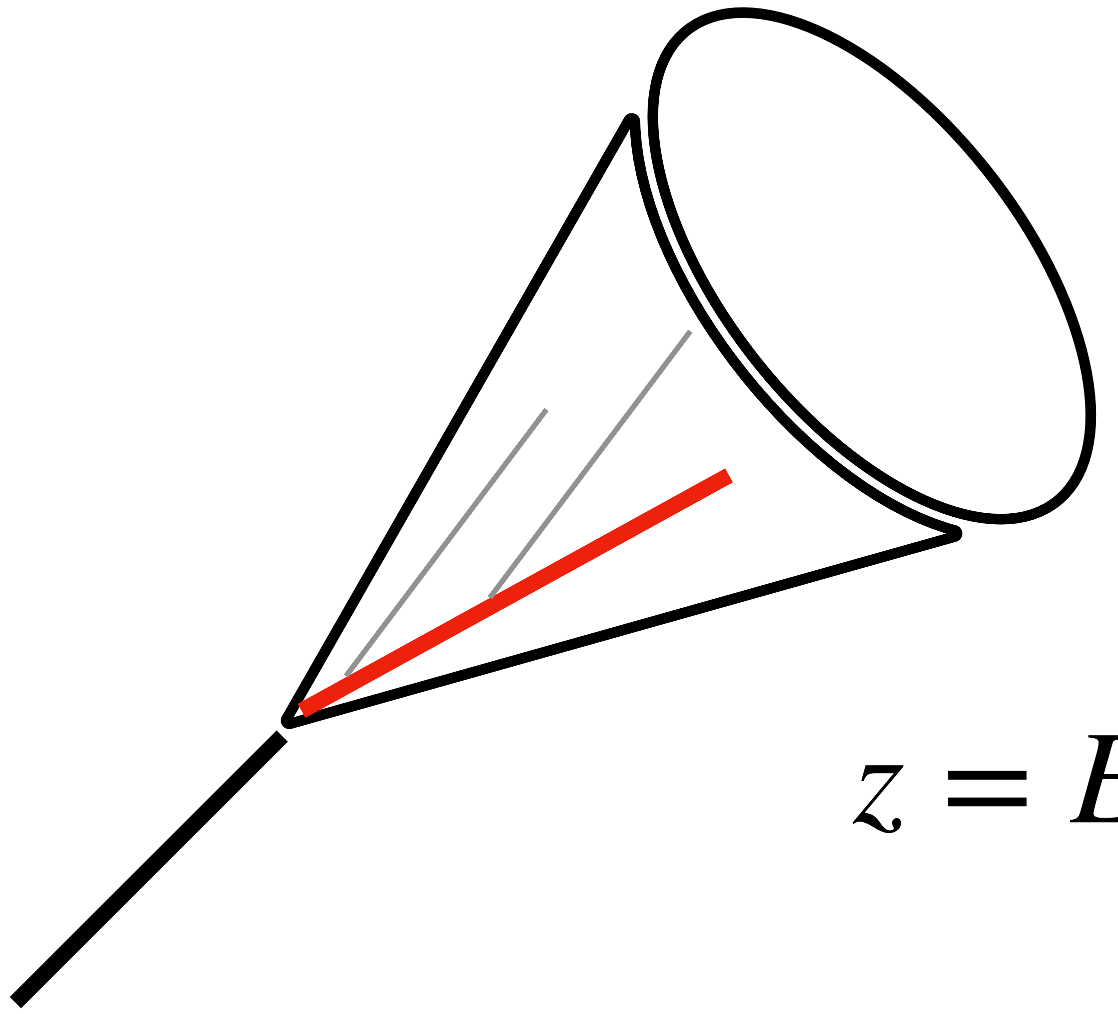
Motivation

Recent attempts using jet

Probing Quarkonium Production Mechanisms with Jet Substructure

Matthew Baumgart[a,1] Adam K. Leibovich[b,2] Thomas Mehen[c,3] and Ira Z. Rothstein[d1]
[1] *Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213*
[2] *Pittsburgh Particle Physics Astrophysics and Cosmology Center (PITT PACC)*
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260
[3] *Department of Physics, Duke University, Durham, NC 27708*

(Dated: June 27, 2018)



$z = E_{J/\psi}/E_J$

Unlike light hadron fragmentation, $D_{q\to J/\psi}(z)$ dominated by perturbative radiations: $E_J \to 2m_Q$

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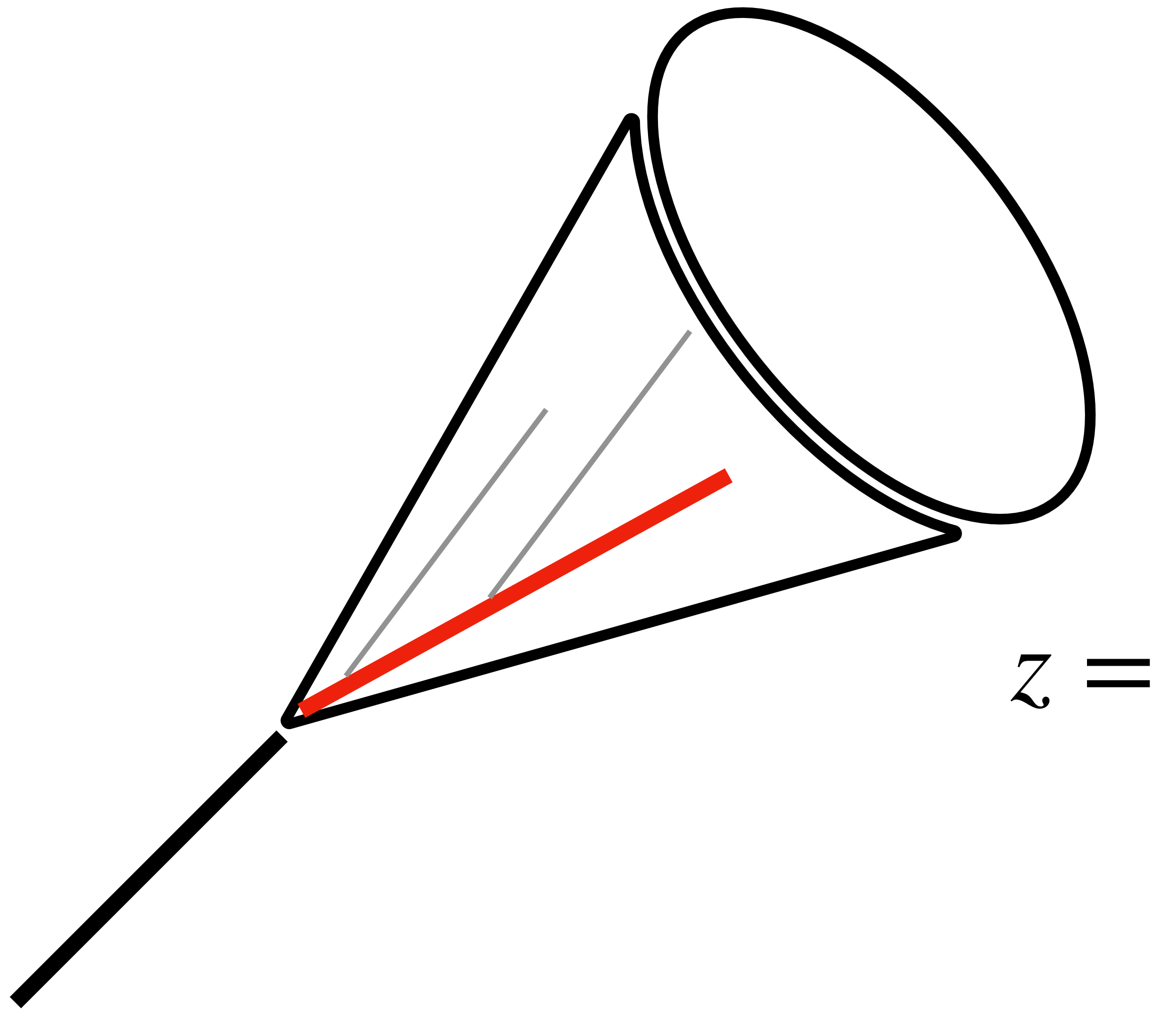

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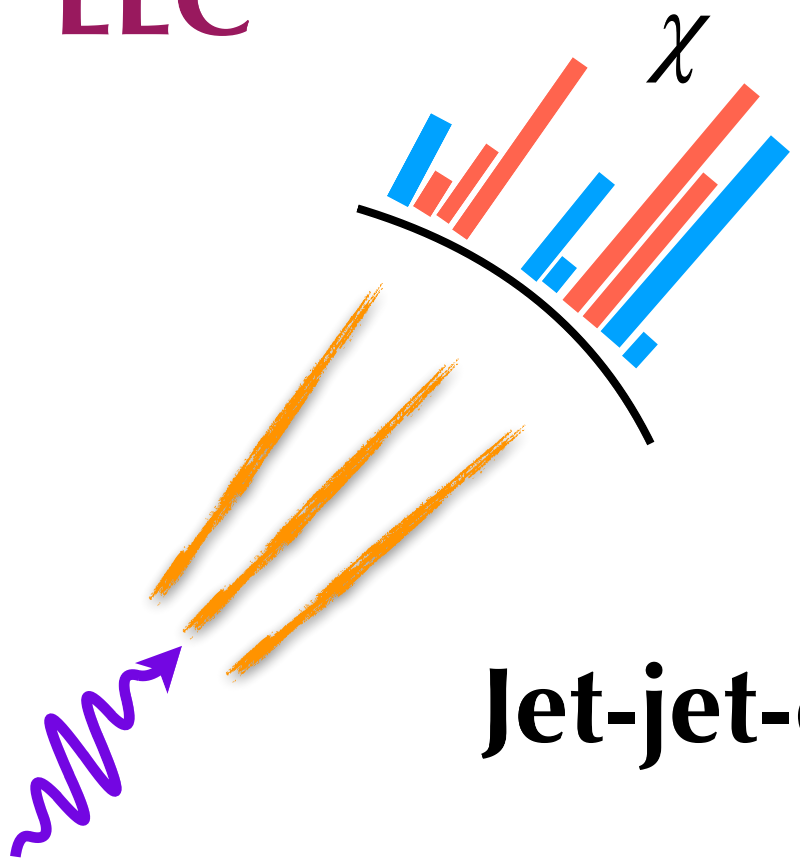
Unlike light hadron fragmentation, $D_{q \to J/\psi}(z)$
dominated by perturbative radiations: $E_J \to 2m_Q$

Chance to "see" hadronziation?

Quarkonium Energy Correlator

Chen, XL and Ma, **PRL** (2024) accepted

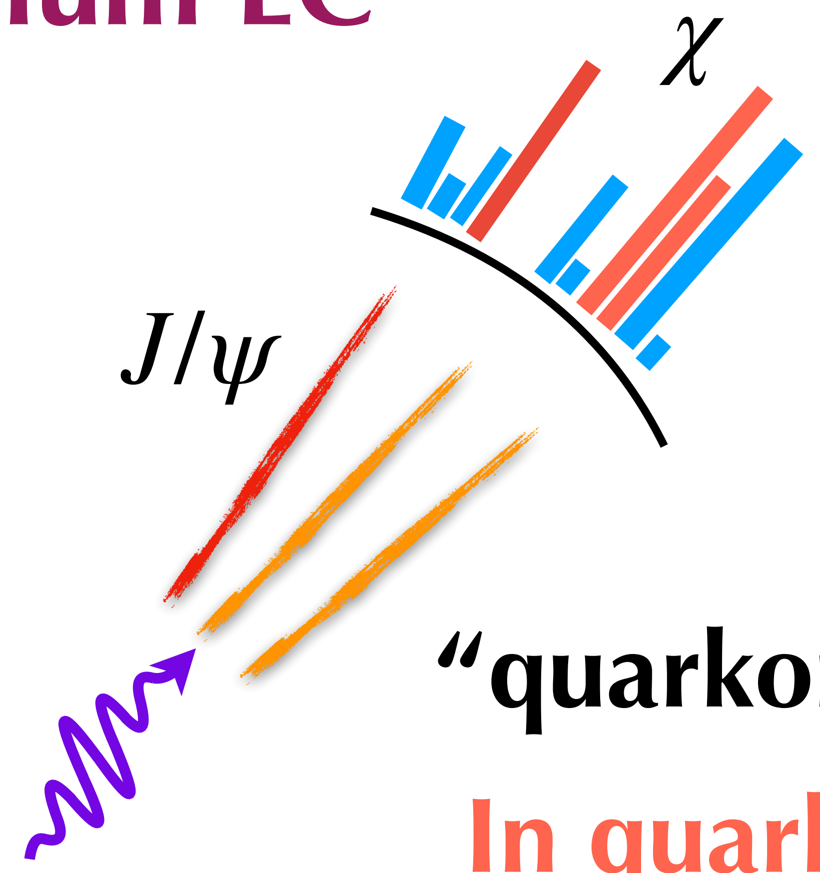
EEC



Jet-jet-correlation

$$\Sigma_{\text{EEC}} = \frac{1}{\sigma}\int d\sigma \sum_{ij} \frac{E_i E_j}{Q^2}\delta(\chi - \theta_{ij})$$

Quarkonium EC



“quarkonim-Jet correlation”

In quarkonium rest frame!!

$$\Sigma_{\mathcal{Q}\text{EC}}(\chi) \propto \frac{1}{\sigma_{J/\psi}}\int d\sigma_{J/\psi}\frac{E_i}{M}\delta(\chi - \chi_i)$$

~ average energy emitted at the angle χ

Quarkonium Energy Correlator

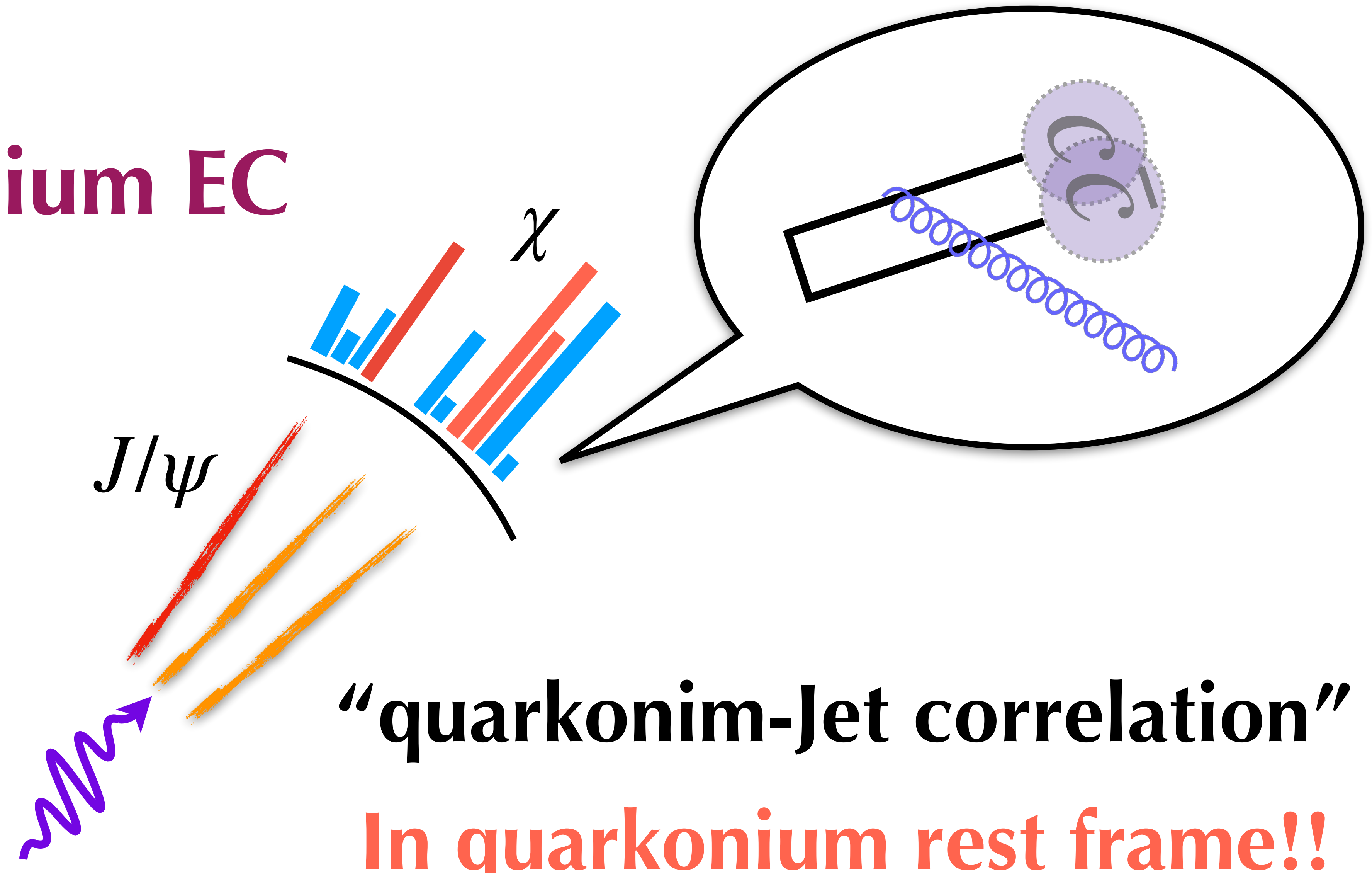
Chen, XL and Ma, **PRL** (2024) accepted

- $\Sigma_{\mathcal{Q}EC} = \Sigma_{\mathcal{Q}EC,P.T.} + \Sigma_{\mathcal{Q}EC,had.}$
  - Hadronization enters as an additive correction, not in the form of convolution
  - Hadronization could be large

$$\Sigma_{\mathcal{Q}EC,P.T.} \sim \alpha_s(\mu)\frac{E(\chi)}{M}E^2(\chi)\langle\mathcal{O}_{\mathbf{1,8}}\rangle,$$

$$\Sigma_{\mathcal{Q}EC,had.} \sim \frac{Mv}{M}M^2v^2\langle\mathcal{O}_{\mathbf{1,8}}\rangle$$

Quarkonium EC



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~ average energy emitted at the angle χ

$$\sim \int^{E_{\max}} \frac{E^2 dE}{2E}\frac{E}{M}\langle\mathcal{O}_{\mathbf{1,8}}\rangle$$

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Chen, XL and Ma, **PRL** (2024) accepted

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Quarkonium EC

for $J/\psi \quad \alpha_s(M) \sim v^2, v \sim 0.5$

$$\Sigma_{\mathcal{Q}EC,had.}/\Sigma_{\mathcal{Q}EC,P.T.} \sim \frac{Mv}{\alpha_s E}\frac{M^2v^2}{E^2} \sim \frac{v^3}{\alpha_s}\frac{M^3}{E(\chi)^3}$$

If $M/E(\chi) \sim 1$

$$\Sigma_{\mathcal{Q}EC,had.}/\Sigma_{\mathcal{Q}EC,P.T.} \sim 50\%\,!$$

Excellent place to study the non-perturbative physics!

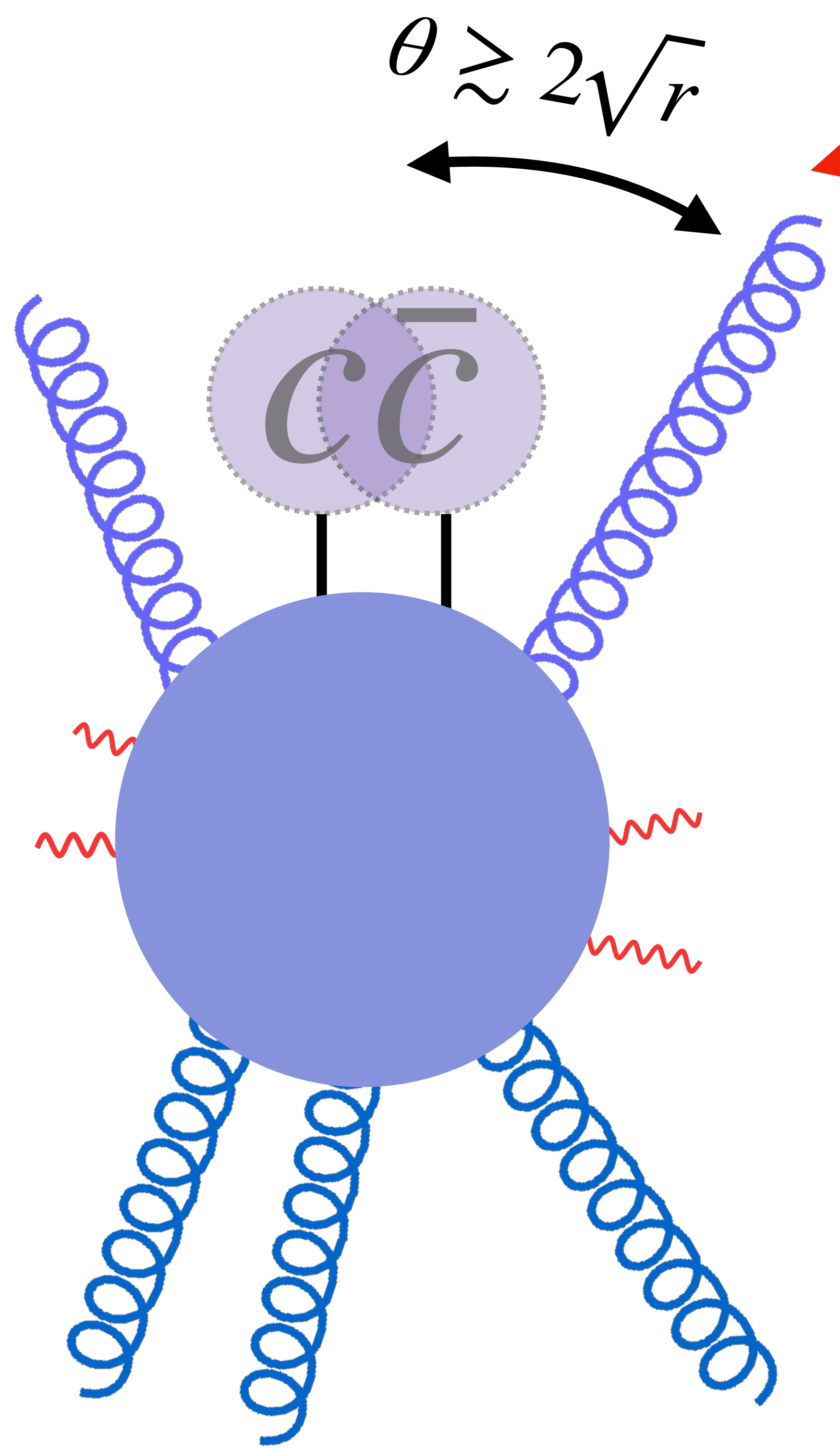
Quarkonium Energy Correlator

Chen, XL and Ma, **PRL** (2024) accepted

Generic J/ψ production configuration in pQCD

COM frame

$$r \equiv \frac{M^2}{\hat{s}} \ll 1$$



$$E_s \sim \mathcal{O}(M), E_{J_{near}} \sim E_{J_{away}} \sim \mathcal{O}\left(\frac{\sqrt{\hat{s}}}{2}\right)$$

dead-cone effects Dokshitzer et al., **J. Phys. G**

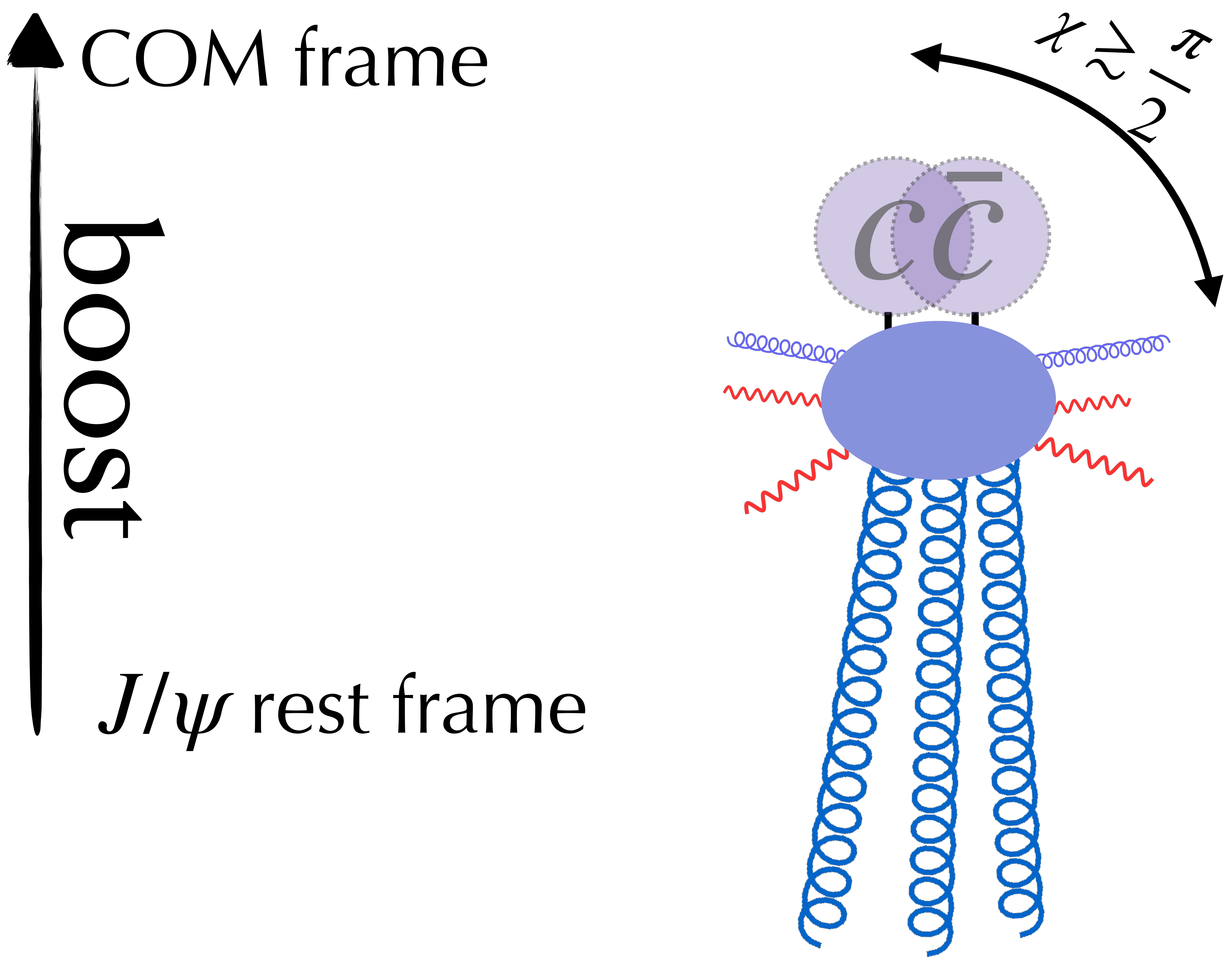
$$d\sigma_{Q\to Qg} \sim \frac{\alpha_s C_F}{\pi}\frac{dE_g}{E_g}\frac{\theta^2 d\theta^2}{[\theta^2+\theta_0^2]^2}$$

$$\theta_0 \sim \frac{M}{E_{J/\psi}} \sim \frac{2M}{\sqrt{\hat{s}}} = 2\sqrt{r}$$

Quarkonium Energy Correlator

Chen, XL and Ma, **PRL** (2024) accepted

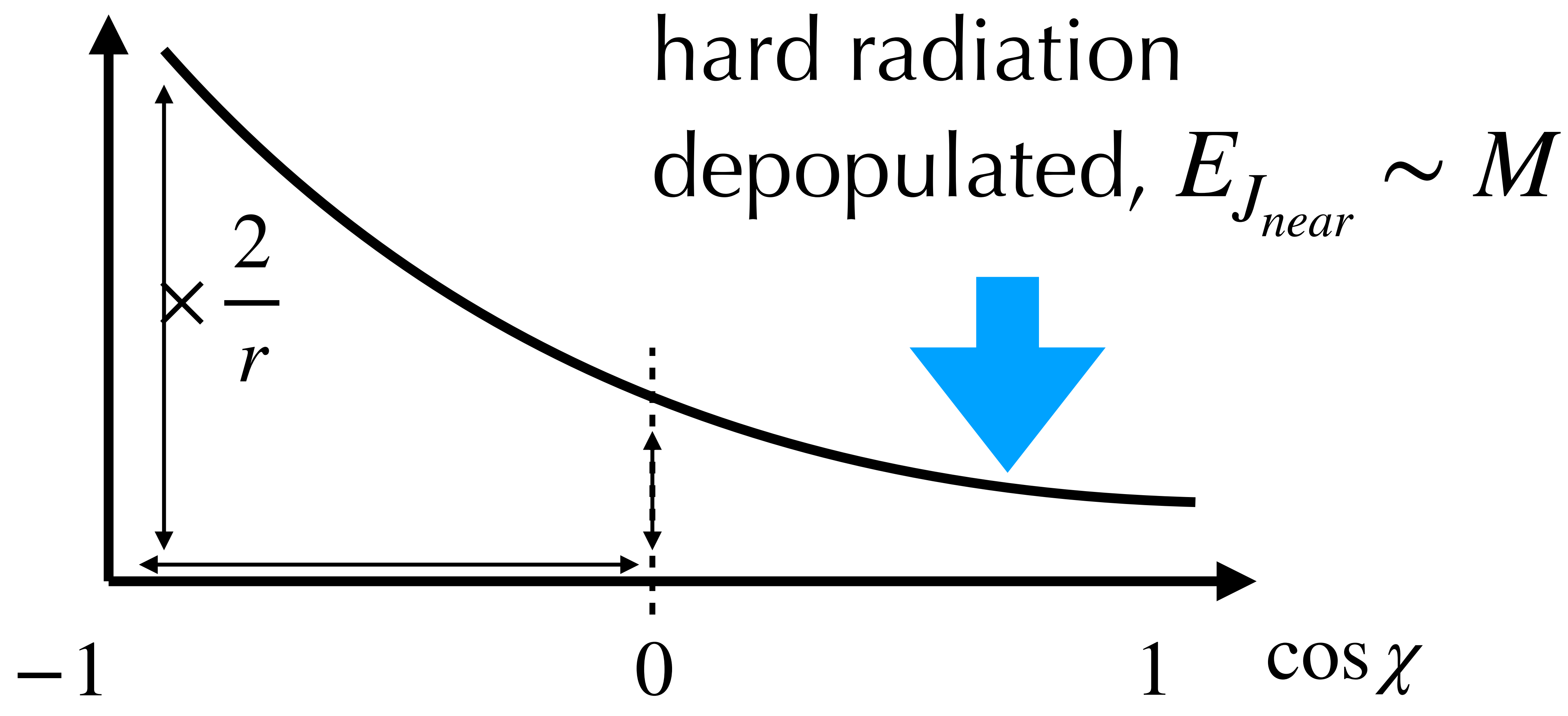
Generic J/ψ production configuration in pQCD



$$E_{J_{near}} \sim E_s \sim \mathcal{O}(M),\ E_{J_{away}} \sim \mathcal{O}\left(\frac{\hat{s}}{2M}\right)$$

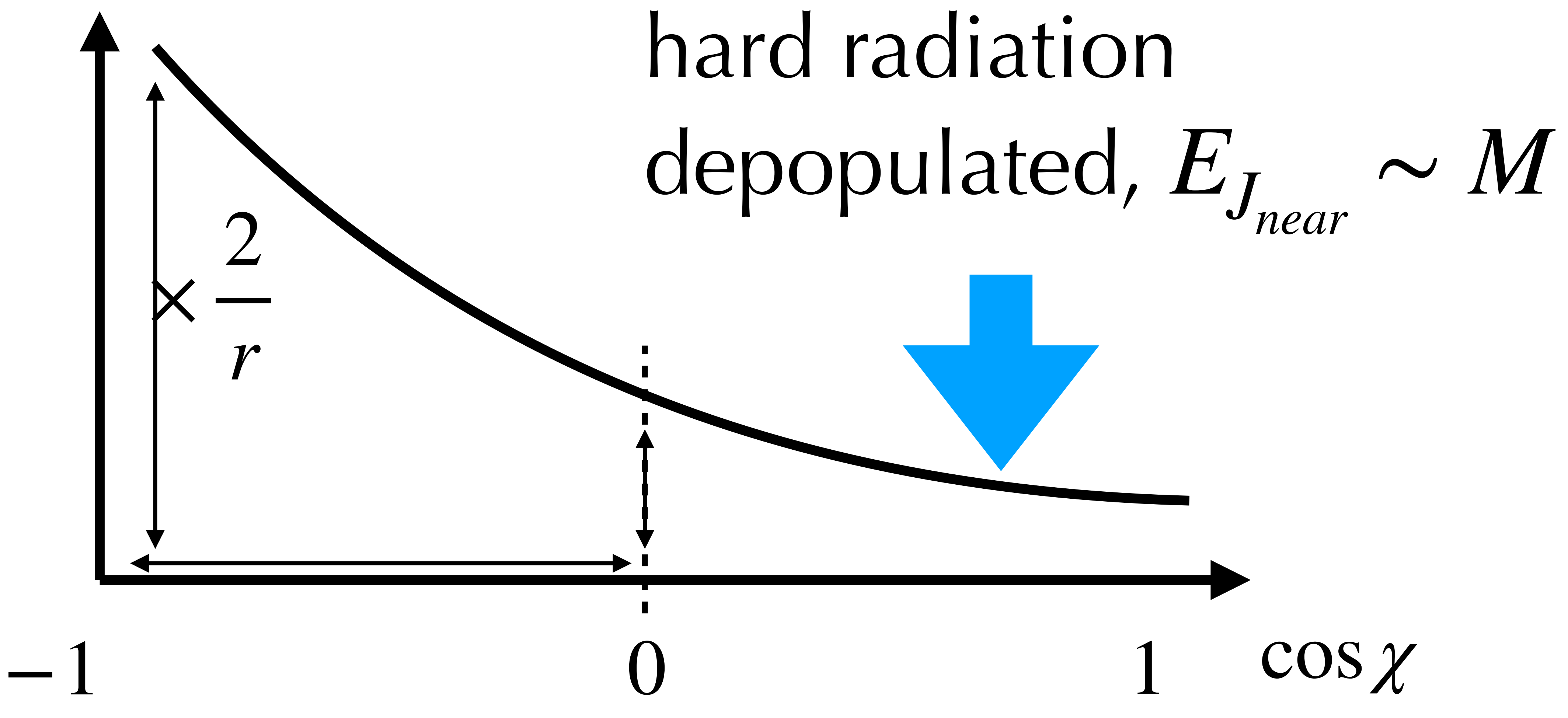
$E_{J_{near}} \sim M$ And further suppressed by dead cone

$$E_{J_{away}}/E_{J_{near}} \sim \frac{1}{2}\text{boost factor}^2 \sim \frac{2}{r}$$



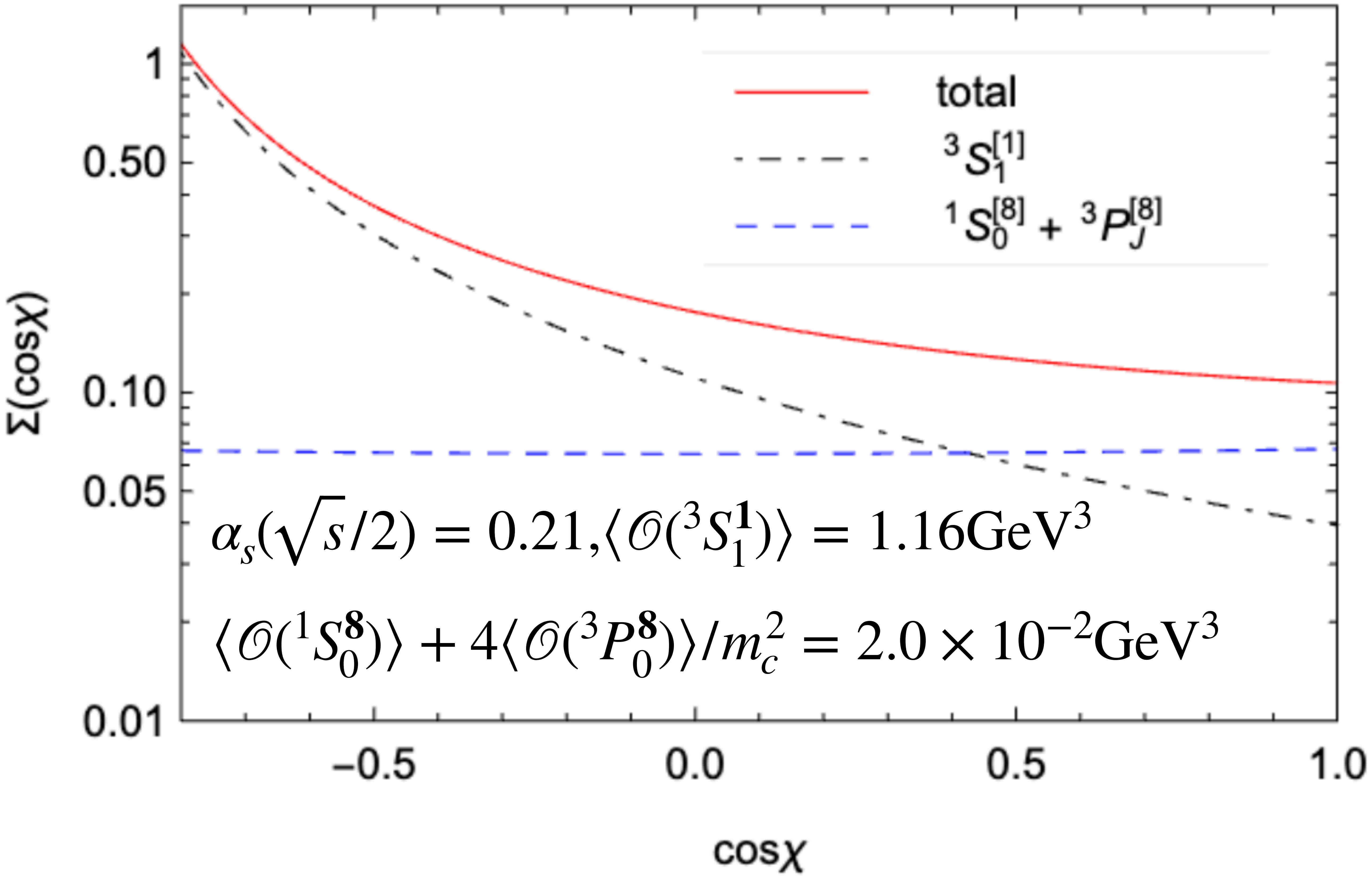
Quarkonium Energy Correlator

Chen, XL and Ma, **PRL** (2024) accepted



Sizable hadronization effect!!

$e^+e^- \to J/\psi + X$



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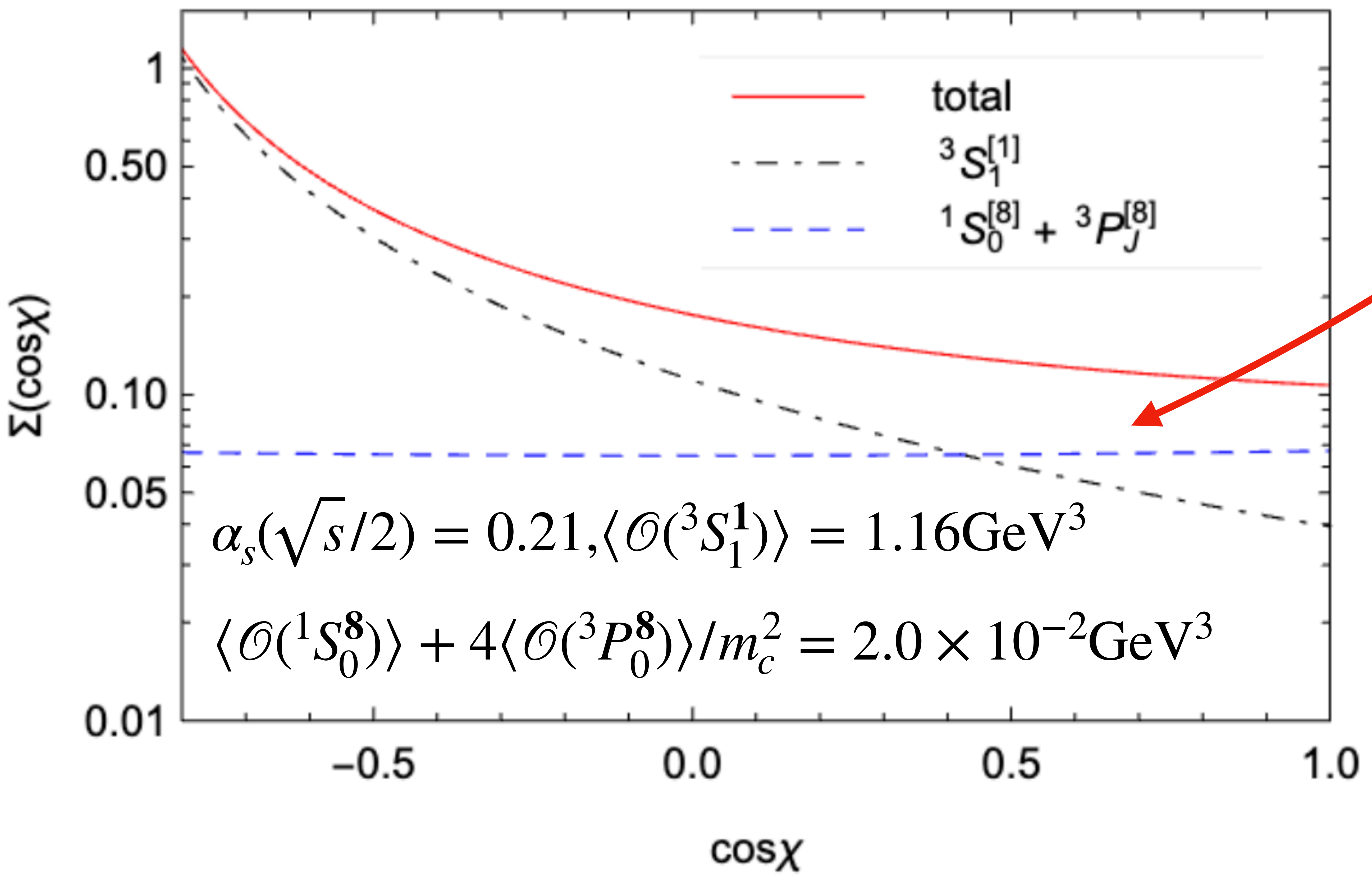
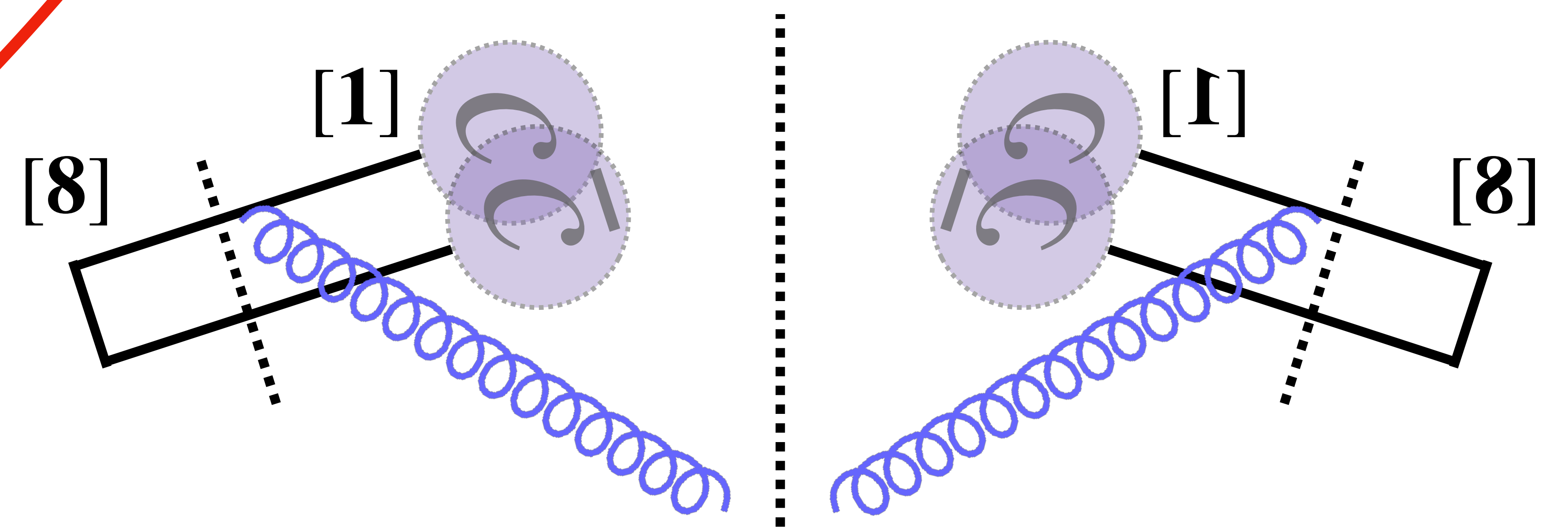
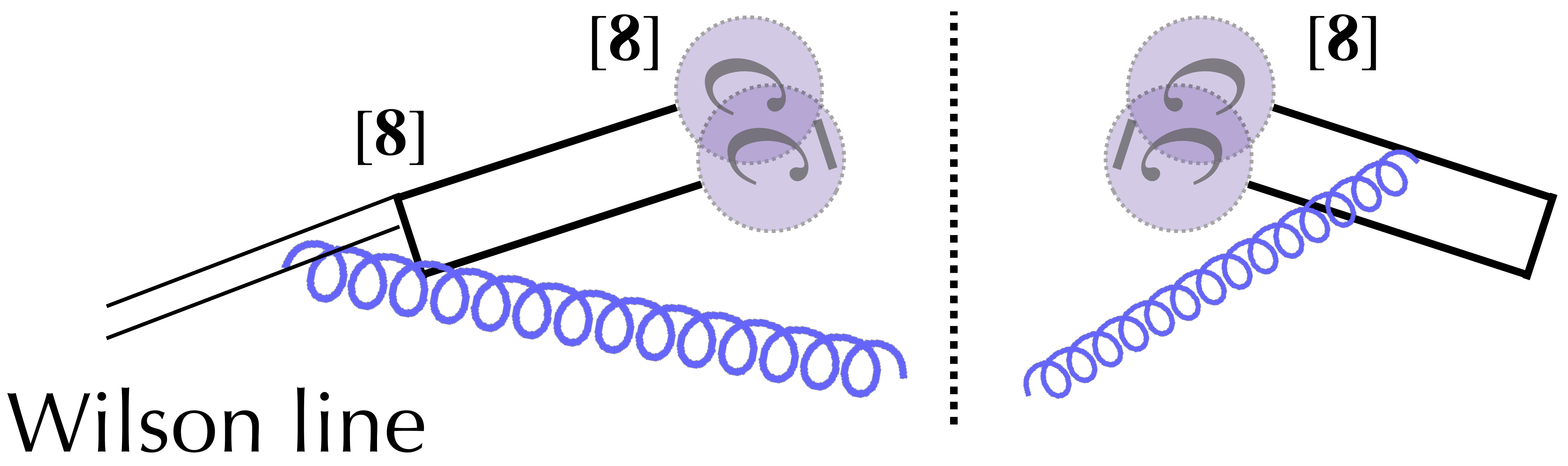


Ignore interference, rotational covariant

$E(\chi) = E$



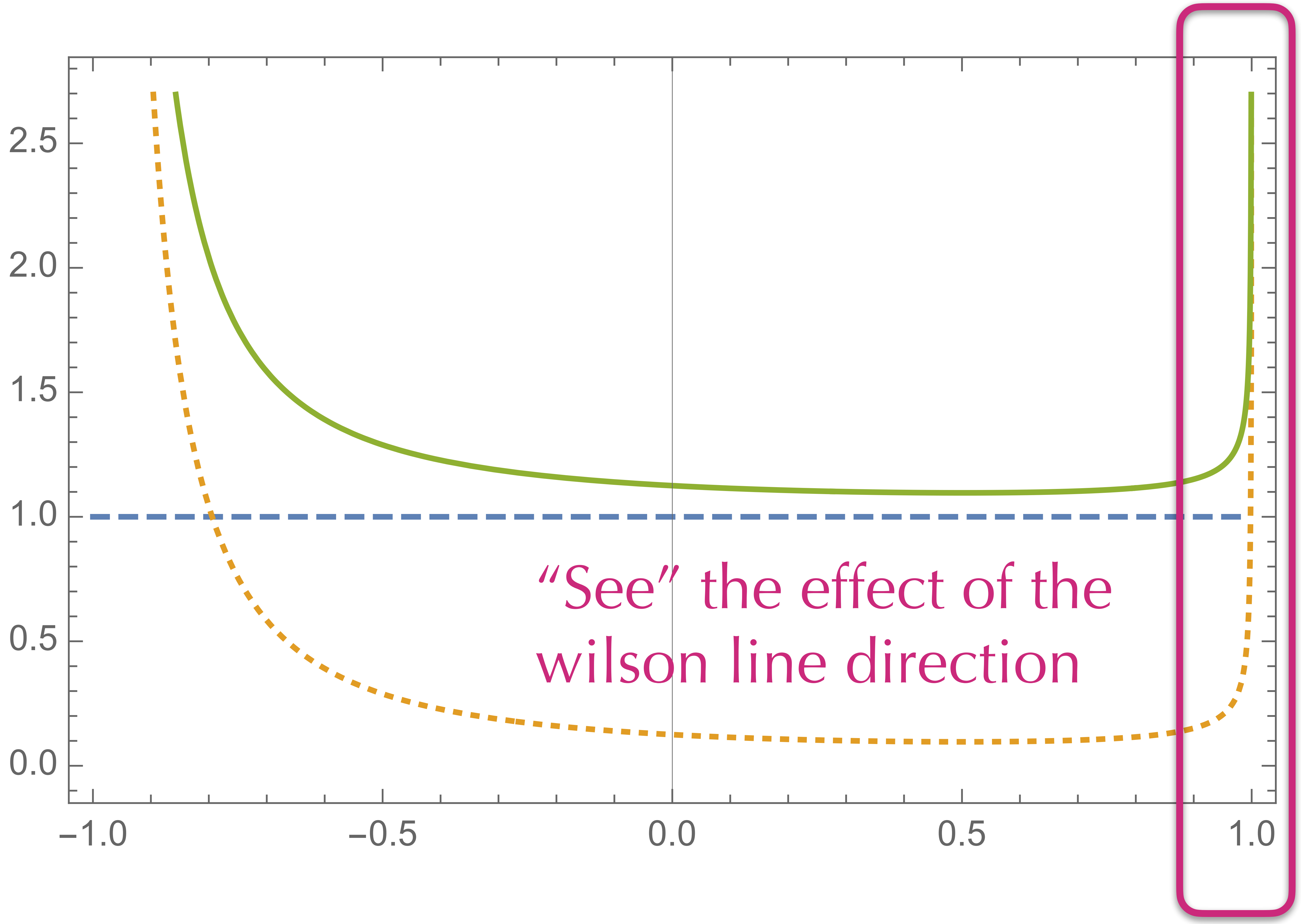
interference, boost covariant $E \sim p_T/\sin\chi$



Quarkonium Energy Correlator

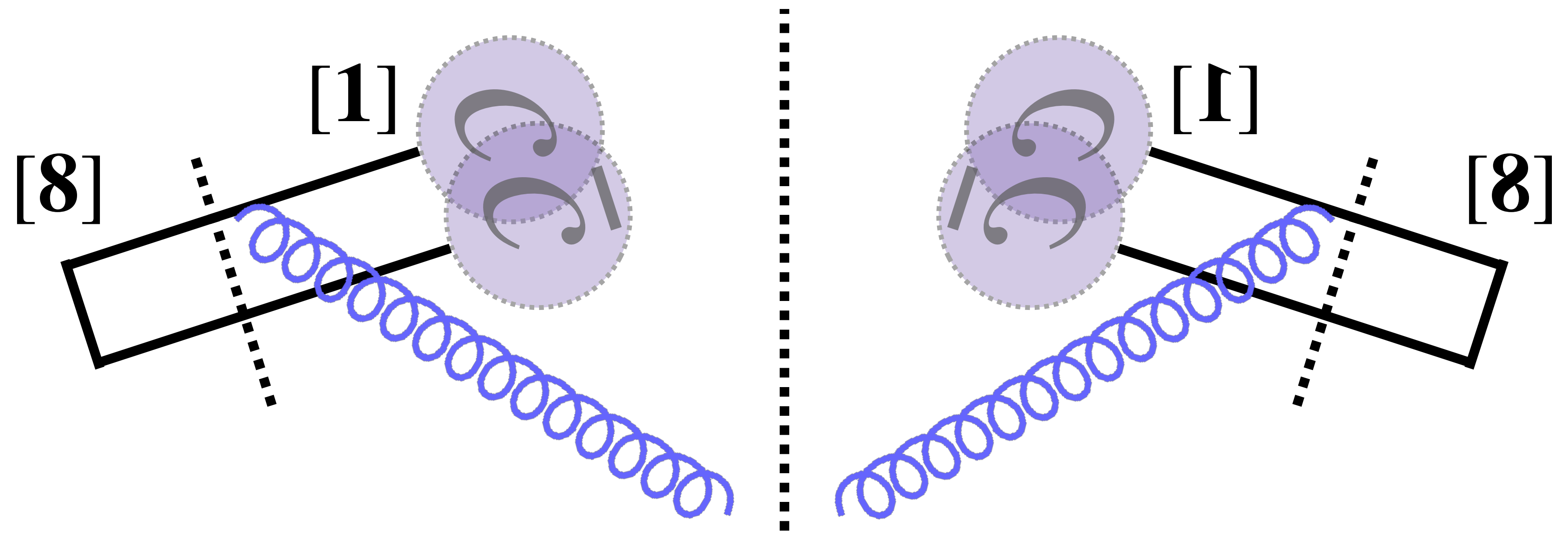
Chen, XL and Ma, **PRL** (2024) accepted

Relative size between non-inter vs interference

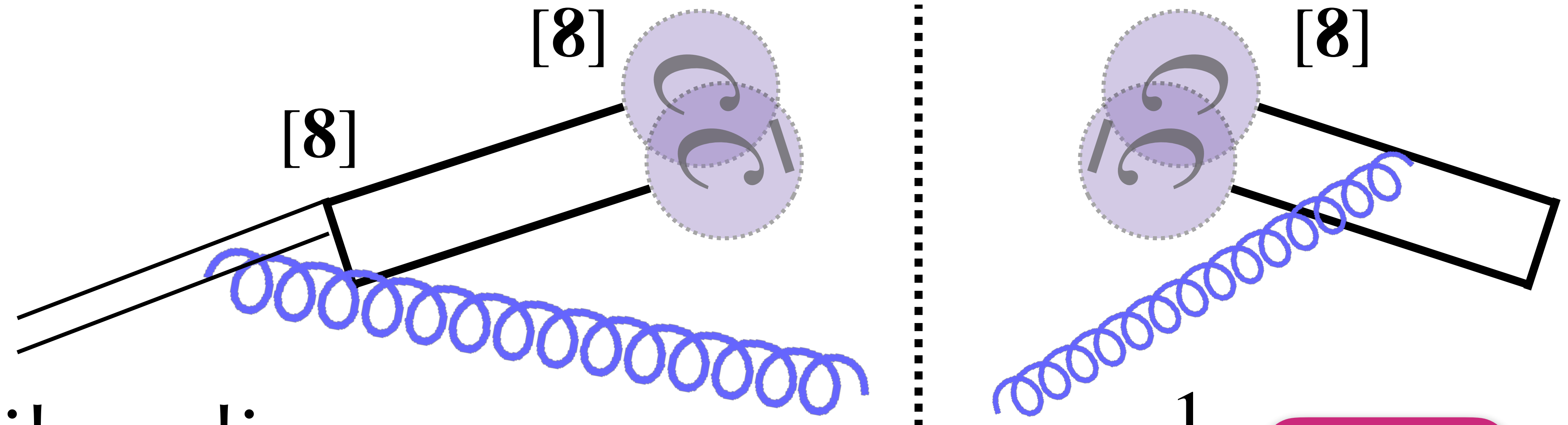


"See" the effect of the wilson line direction

Ignore interference, rotational covariant



interference, boost covariant

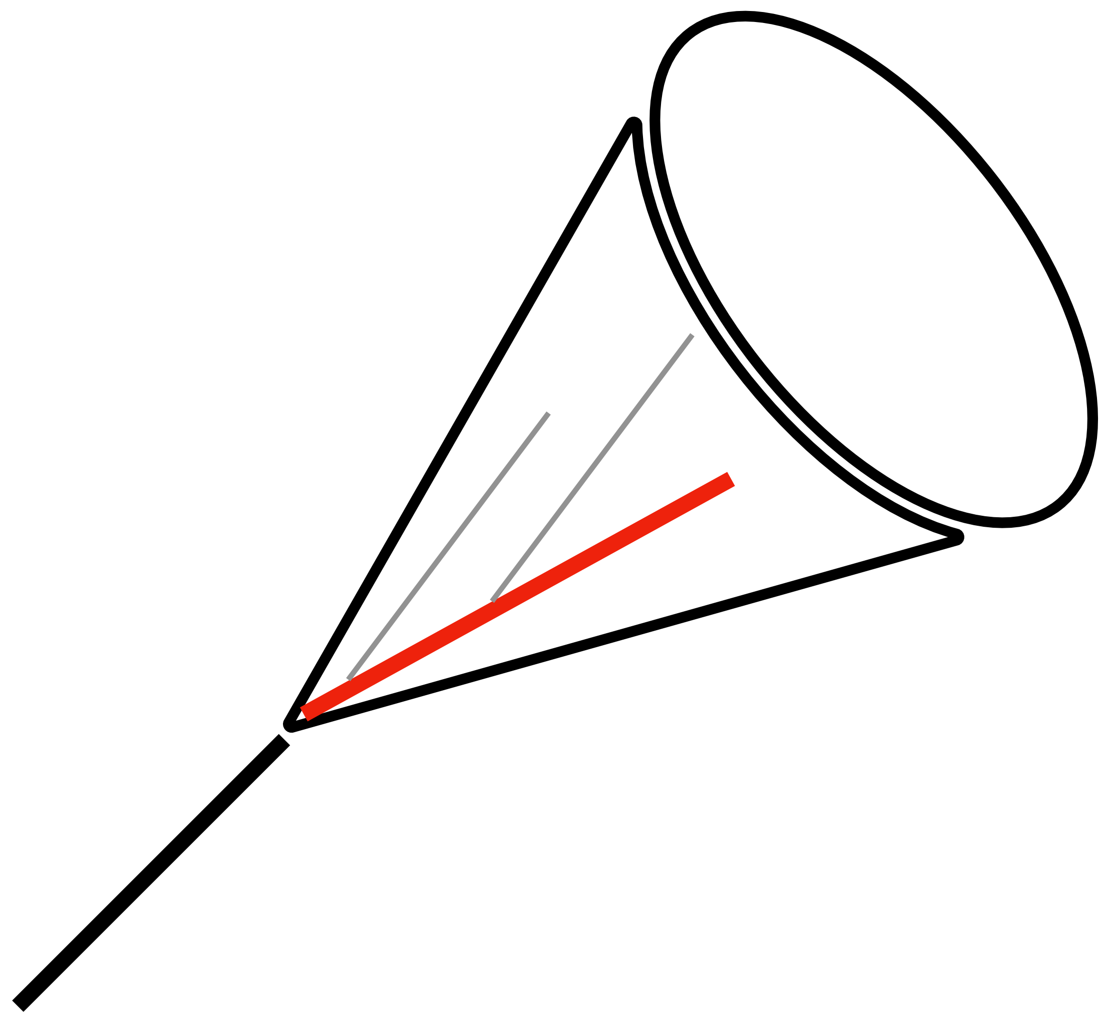


$$\sim \frac{1}{(1+\cos\chi)\sin\chi}$$

Quarkonium Energy Correlator

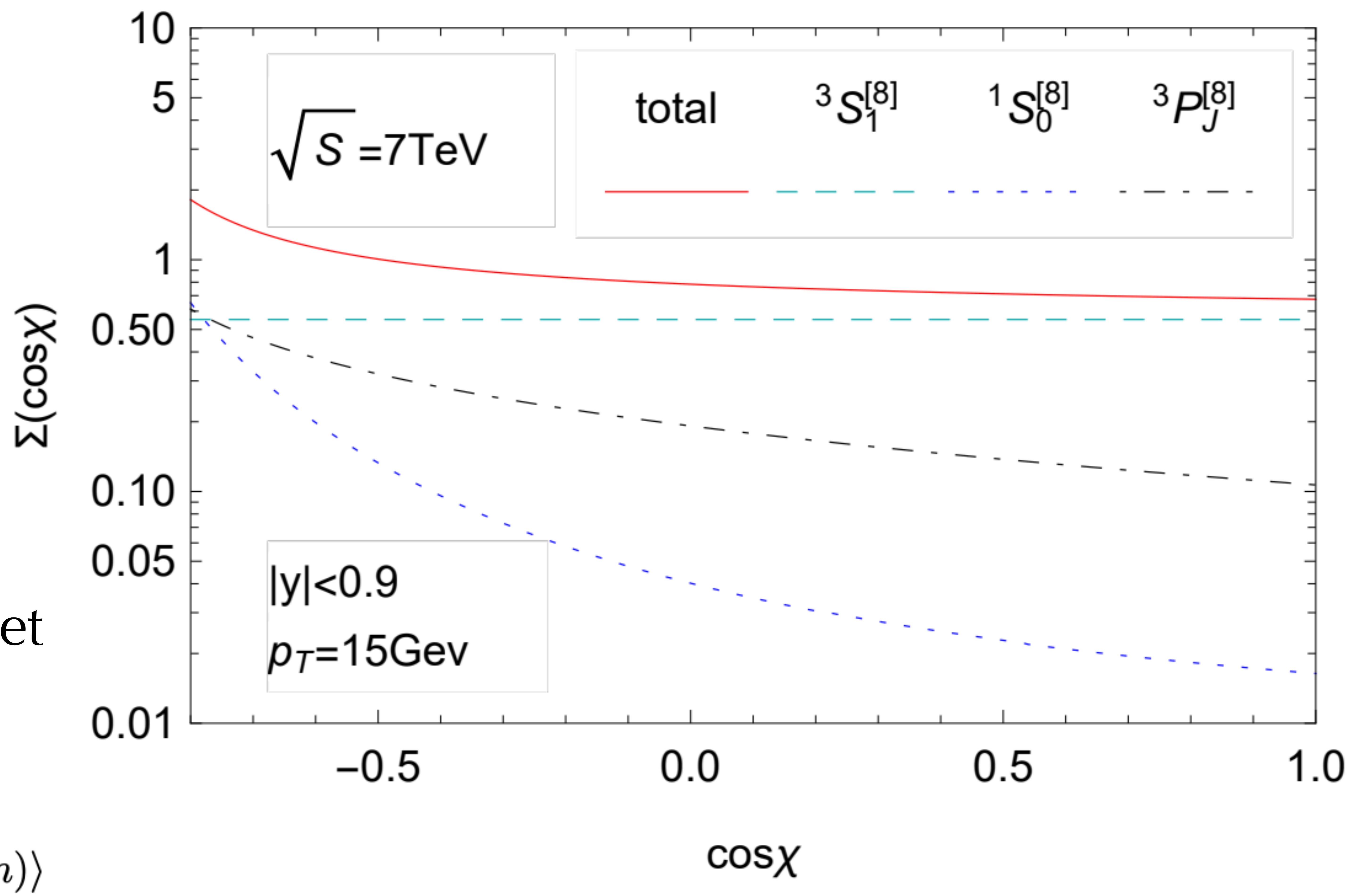
Chen, XL and Ma, **PRL** (2024) accepted

Similar story happens to *pp*



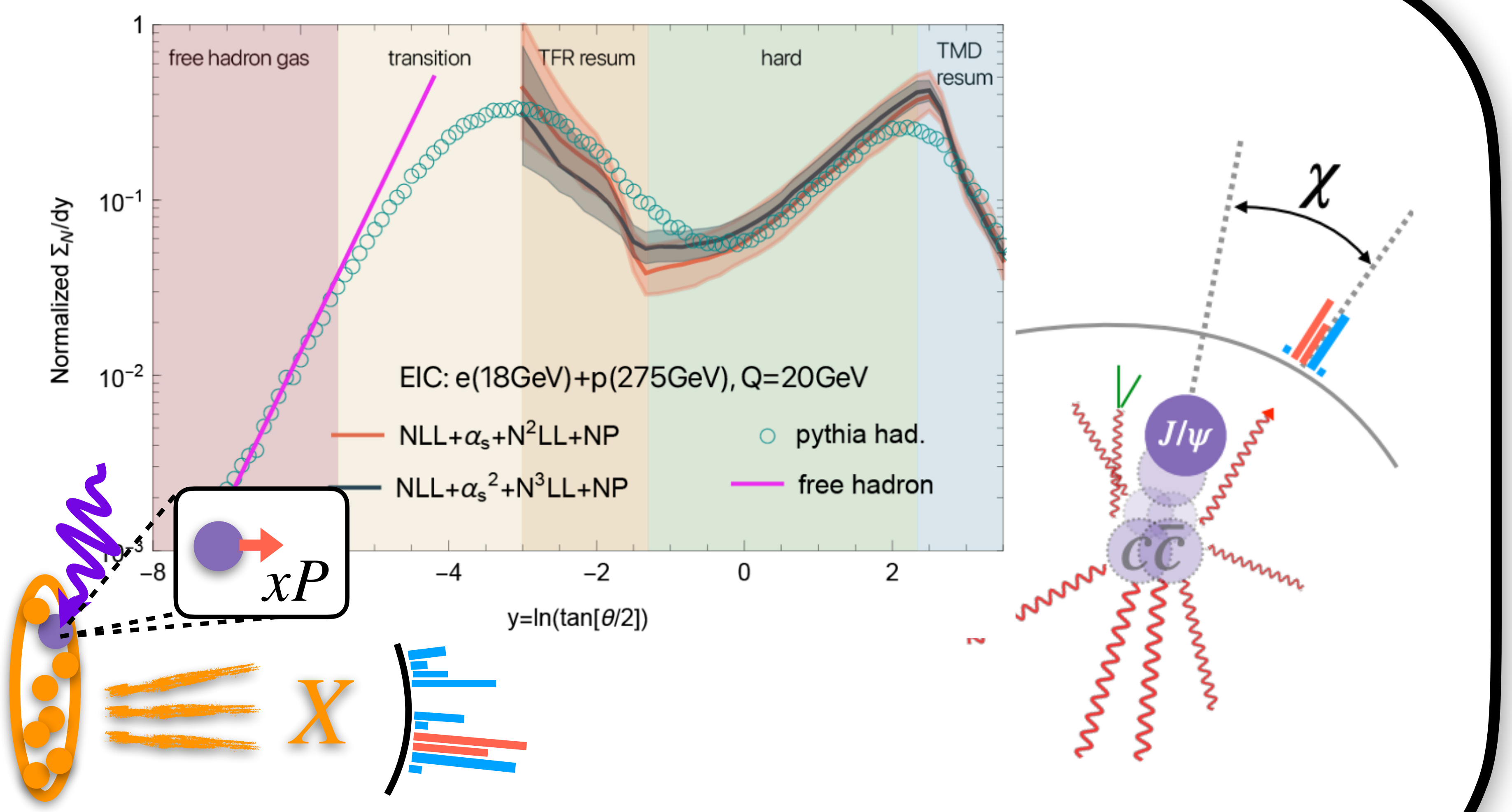
Preselecting particles inside a fat jet

$$\Sigma(\cos\chi) = \sum_n \int_0^1 dz d\hat{\sigma}_{A+B\to g+X}(\hat{p}/z, \mu_F) \times \hat{D}_{g\to c\bar{c}[n]}(z, \cos\chi, \mu_F)\langle \mathcal{O}^{J/\psi}(n)\rangle$$

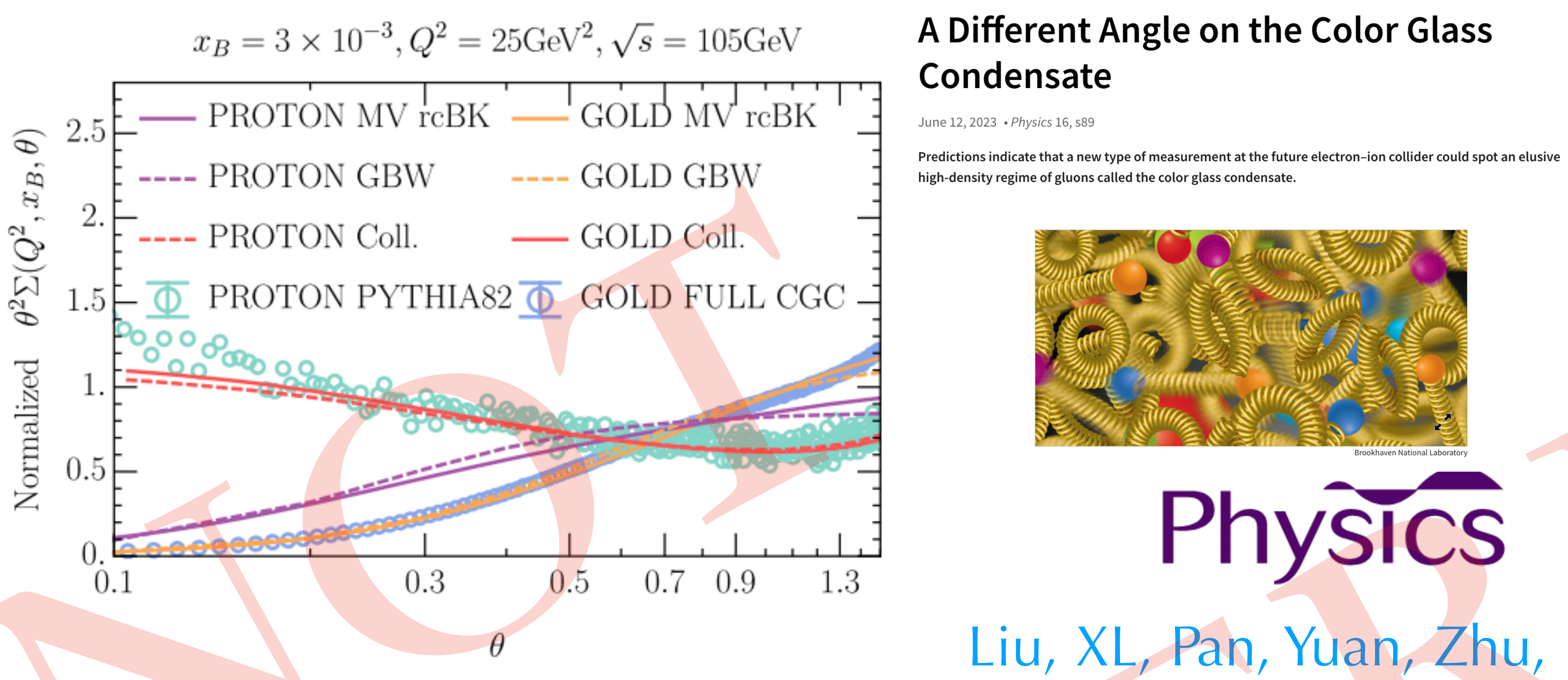


Conclusions

This Talk

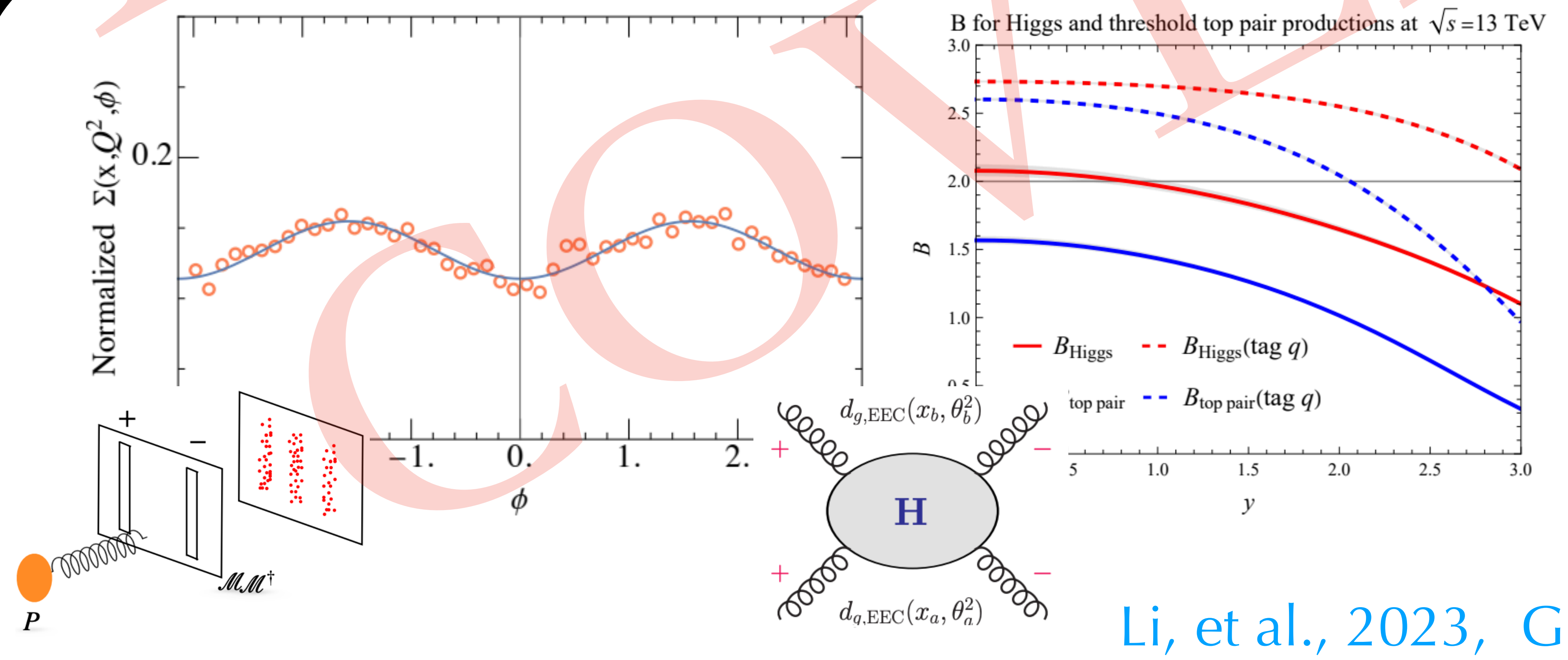


- Properties
- A new tool for NP physics



NEEC as a promising probe of the gluon saturation

Liu, XL, Pan, Yuan, Zhu, PRL 2023



Spinning gluon, and test bell inequality

Li, et al., 2023, Guo, et al., 2024

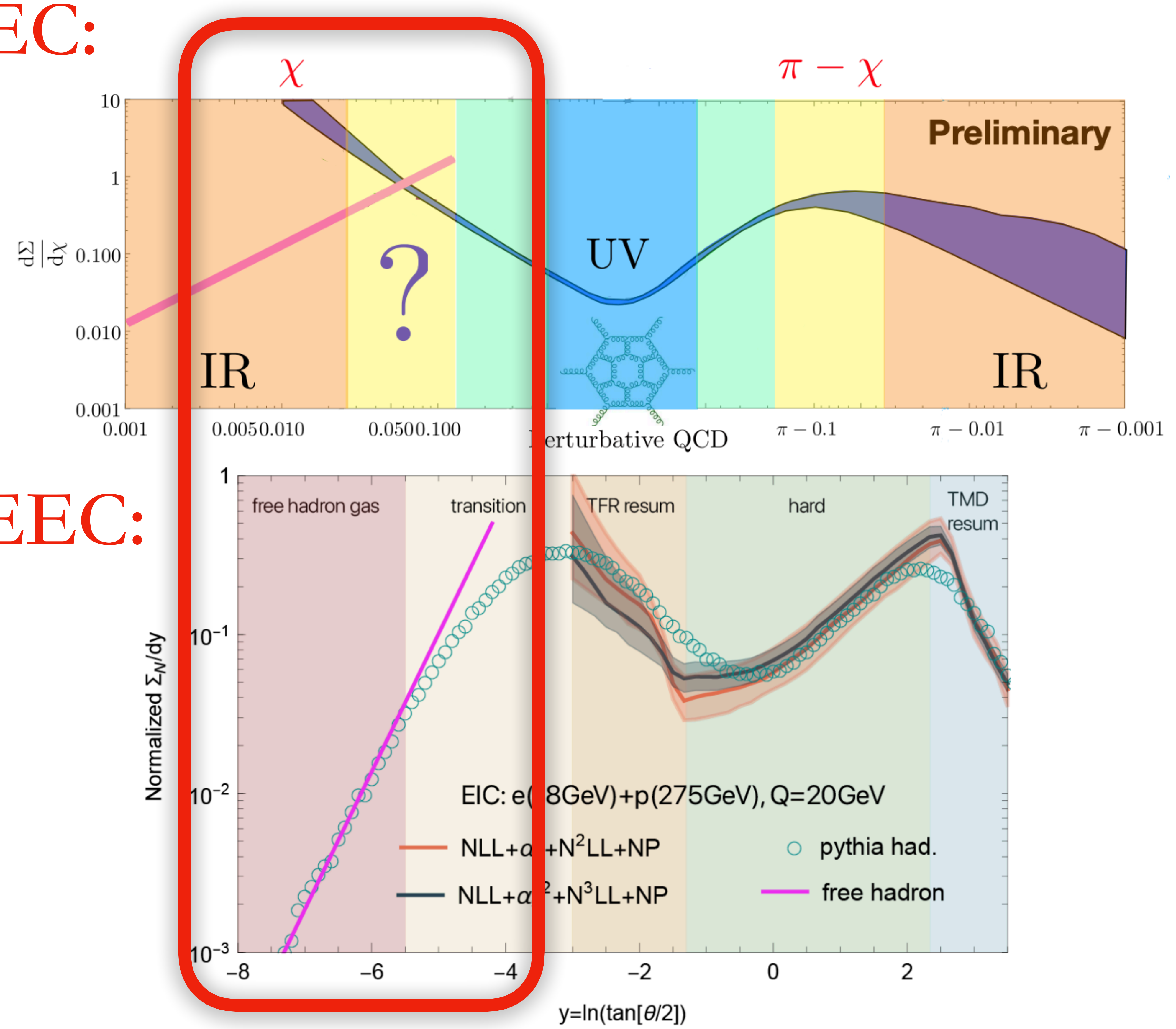
NOT COVERED

Outlook

New perspective to the NP hadron structures ?

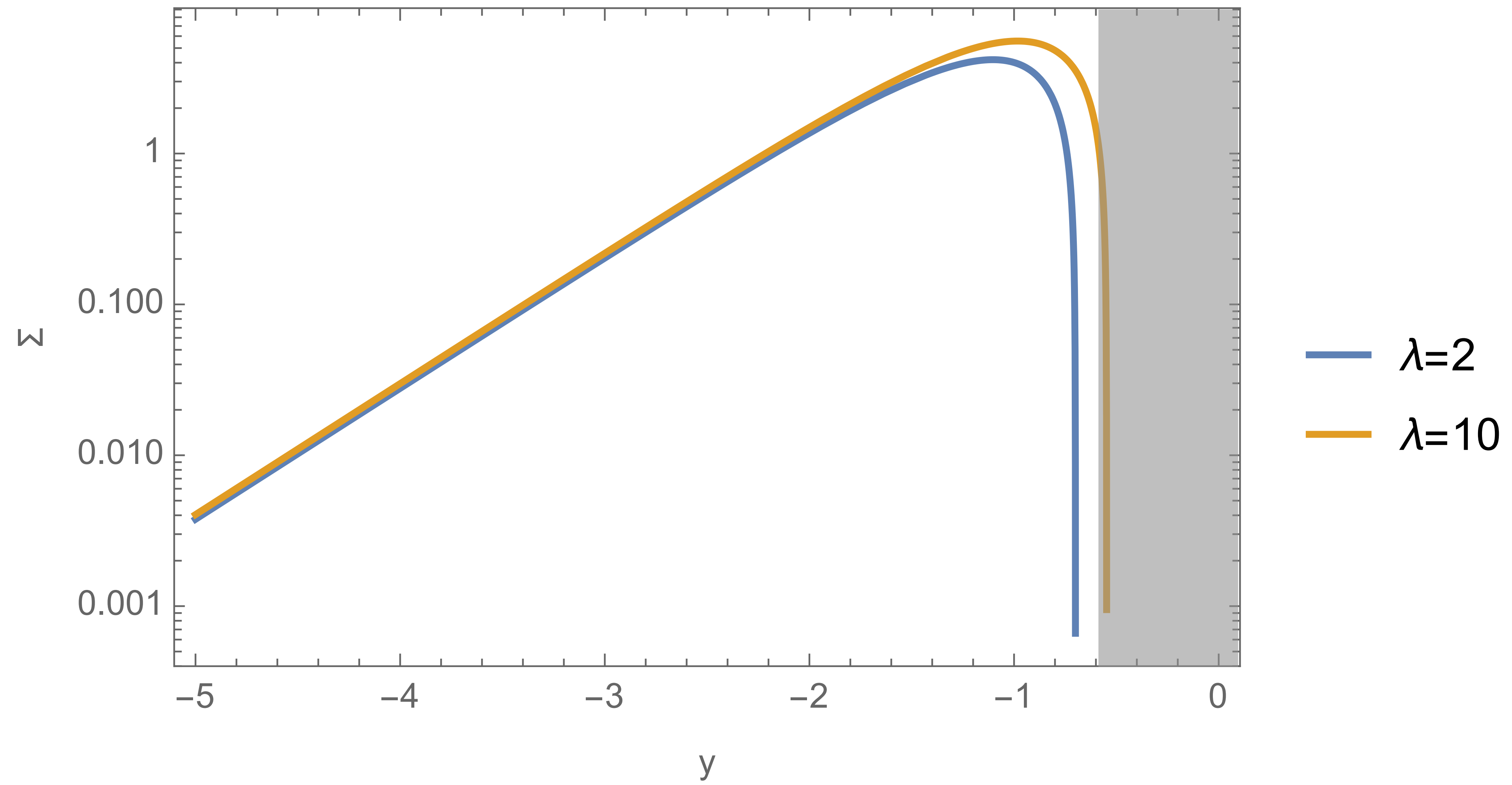
EEC:

NEEC:

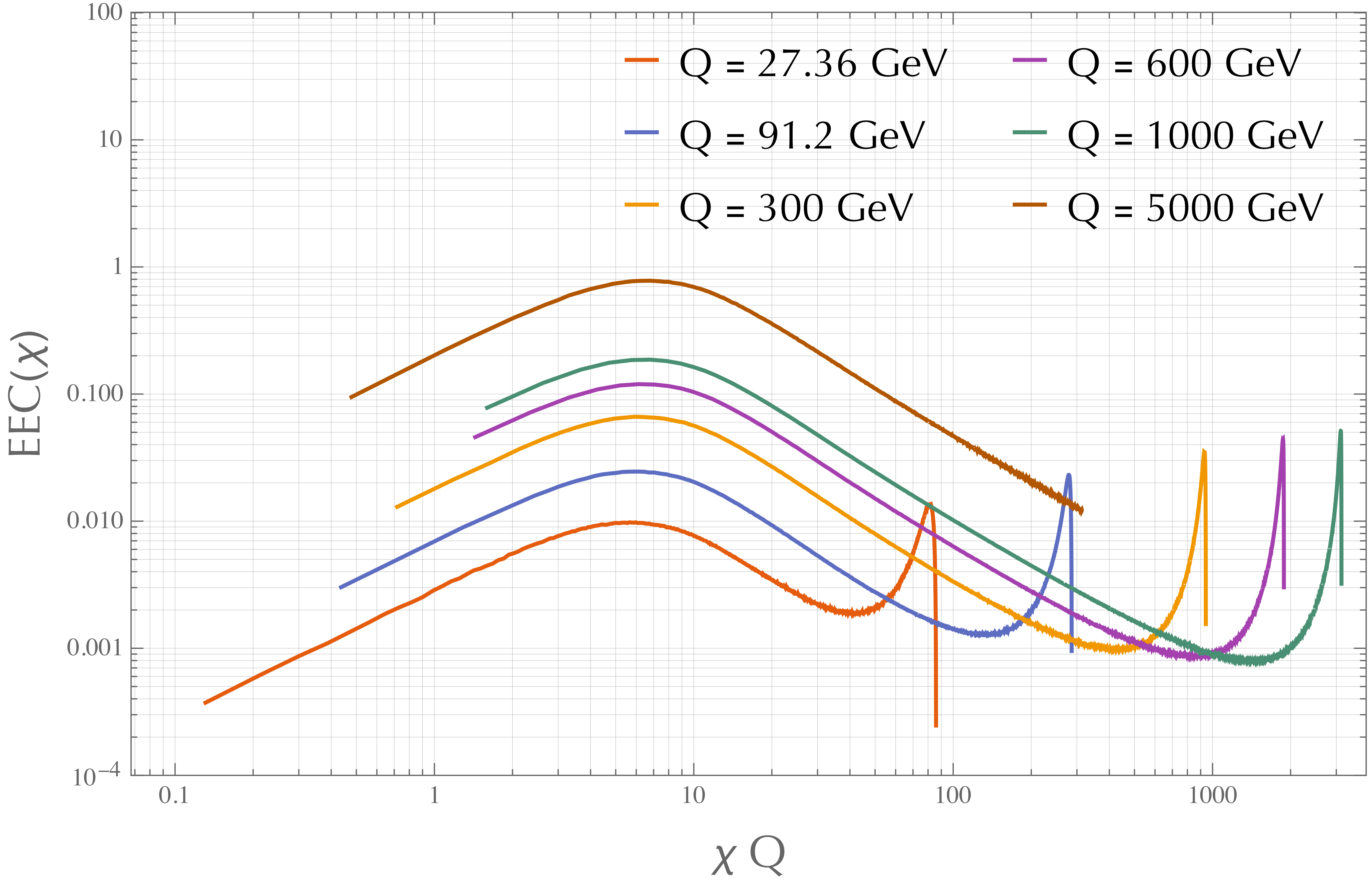


$$\langle \mathcal{E}(\vec{n}_1')\mathcal{E}(\vec{n}_2')\rangle = (\frac{q^0}{4\pi})^2 \left[1 + \frac{6\pi^2}{\lambda}(\cos^2\theta_{12} - \frac{1}{3}) + \cdots\right]$$

Hofman, Maldacena, 2008



Thanks



Q = 27.36 GeV
Q = 91.2 GeV
Q = 300 GeV
Q = 600 GeV
Q = 1000 GeV
Q = 5000 GeV
EEC(χ)
χ Q
100
10
1
0.100
0.010
0.001
10^{-4}
0.1
1
10
100
1000